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Simulation-based impact assessment framework for driving restriction zone policies☆

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ABSTRACT

Conventional methods for predicting emissions predominantly rely on site data-driven regression models, thus failing to evaluate mobility impacts of transport policies. This research demonstrates how agent-based simulation has been used to assess ex-ante impacts of one of these policies, driving restriction zone, enabling policymakers to evaluate and refine such interventions during the design phase. The proposed framework examines impacts on mobility and the environment at various aggregation levels. The case study assesses two policy scenarios with varying tolerance levels for road network access by unauthorized non-residents in residential areas; each one-fifth of non-local drivers is restricted every fifth weekday, based on license-plate digits. The findings reveal that both policies reduce car usage, albeit with a slight cost to traffic efficiency. Additionally, the policies contribute to a notable decrease in CO_2 emissions and local air pollutants across all agent groups, citywide, and more locally.

1. Introduction and literature review

1.1. Background

The expansion of personal transportation excessively utilizes roadway resources. Moreover, the efficiency of private transportation in recent years has resulted in traffic congestion, significant local air pollution, and increased greenhouse gas (GHG) emissions in urban areas. These emissions pose a threat to both the climate and public health (Nieuwenhuijsen and Khreis, 2016). In response, local governments have implemented various policies over the last two decades to encourage the adoption of sustainable mobility options over the use of private vehicles.

In the early 1990s, car-free developments emerged in Germany and Austria, mainly focusing on prohibiting motorized traffic circulation in residential areas (Melia, 2010). The aim of this implementation is to alleviate congestion and reduce traffic emissions.

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In recent years, hundreds of European cities have deployed similar concepts of urban access regulations. A well-known strategy is the implementation of low emission zones (LEZ) (Sadler Consultants Europe GmbH, 2017). The Low Emission Zone (LEZ) scheme restricts or outright prohibits vehicle entry into designated parts or the whole city, employing typical regulatory strategies such as restricting access to specific times of the day or certain vehicle types, along with adjustments to speed limits (Victoria Transport Policy Institute, 2014). Additionally, dedicated areas have established so-called "super blocks" and "ultra-LEZ", to create green space and prioritize walking and cycling (Ding et al., 2022; Müller and Reutter, 2020; Ziemke et al., 2022). Many city governments have demonstrated improvements in air quality following the implementation of LEZ (Bernard et al., 2020; Commission, 2014; Ricci et al., 2017). Various studies have also assessed the effects of LEZ strategies. For example, Dias et al. (2016) suggested that PM_{10} and NO_2 emissions from individual automobile mode decreased dramatically in LEZ (by 63% and 52%, respectively), while the amount of emissions at the city level increased, leading to deterioration in air quality. In contrast, other studies have reported air quality improvements at both neighborhood and city level. For instance, Fensterer et al. (2014) investigated the effects of commercial vehicle restrictions in Munich, Germany, and found that the PM_{10} concentration ratio was reduced by 6.8% to 19.6% in the policy implementation area and there was an approximate 10% decrease in PM_{10} levels citywide following the introduction of these measures.

1.2. Literature review and research gaps

Building upon the reviewed literature on LEZ implementation and related sustainable transport policies, several critical research gaps emerge that warrant further investigation. The identified gaps can be broadly categorized into two areas: first, limitations in existing policy designs and implementations, and second, methodological shortcomings in policy assessment frameworks. These gaps will be systematically elaborated in the following sections, beginning with policy-specific challenges in LEZ and driving restriction policies, followed by methodological limitations in current assessment approaches. Understanding these gaps is crucial for developing more effective policies and more comprehensive evaluation tools.

1.2.1. Research gaps on measures

- **RG 1: The scale and level of restriction for the policies**
  Tu et al. (2021) suggested that the severity level of restriction and the spatial scale of the LEZ have different impacts on NO_2 concentration. Specifically, the proportion of restricted vehicles has a significantly higher impact than the spatial scale of the LEZ, and the effects of scale increase with the proportion of restricted vehicles. Unfortunately, no other papers validates this finding. In addition, further investigation is also required to evaluate different level of road access restrictions of the policies (i.e., whether vehicles are allowed to travel on main roads within these zones), as there are currently no studies specifically addressing this aspect.
- **RG2: The policy implications for different groups of people**
  The existing literature above has yet to conclusively determine the effects of the policies on different groups of individuals, including residents, workers, and visitors. To cater to all groups of people, it is crucial to examine the effects of driving restrictions on traffic patterns and travel behaviors of different population segments.
- **RG3: The long term effects of the policies**
  The driving restriction policy (DRP) primarily benefit local residents by reducing motorized traffic in their vicinity. Several empirical studies have shown that while the conventional driving restriction policies can reduce traffic only within the designated area, they boost traffic in surrounding areas in the short term due to detours (Elbert and Friedrich, 2019; Lurkin et al., 2021; Sleiman, 2021). However, it remains uncertain whether this effect will persist in the long term and lead to a significant modal shift from cars to alternative transportation modes (Sleiman, 2021).
- **RG4: Increased car purchase rate due to driving restrictions**
  In Mexico, China (Beijing Municipal People's Government, 2024) and other countries, odd-even traffic restriction strategies have been implemented. However, these strategies have led to people purchasing second cars with different license plates to circumvent the restriction (Lyu, 2022). Soto et al. (2023) also confirm this and states that this measure can be counterproductive in the long term as it may incentivize the purchase of a second vehicle, often a used one, which tends to be more polluting.

Our proposed driving restriction policy, inspired by the license plate driving restriction policy (LDRP) implemented in Beijing and Mexico City, aims to tackle the problem of high emissions in cities with a less restrictive approach. Unlike the extensive restriction areas and high restriction levels seen in these cities, our policy targets a smaller scale with fewer restrictions. Consequently, this research introduces the concept of a driving restriction zone (DRZ), an advanced policy derived from merging the LEZ and DRP strategies. This approach involves regulating access to a small, monitored residential area to diminish emissions and encourage environmentally friendly transportation methods, such as mass transit, cycling, and walking.

1.2.2. Research gap on the methodology

Through a comprehensive literature review, following the approach of Zhi et al. (2024), we compared several studies across multiple dimensions including policy types, modeling techniques, analysis resolution, and evaluation indicators. This comparative analysis results are summarized in Table 1.

Table 1
Summary of literature review on related measures.

Paper	Policy	Data source	Model	Highest resolution	Traffic efficiency	GHG emissions	Local air pollution	Distribution
Poulhès and Proulhac (2021)	LEZ	Calibrated simulated fine mapping of pollutant concentrations, travel survey	Traffic assignment model	Demographic group	No	No	NO_2	–
Tu et al. (2021)	LDRP	Site data measured by urban background stations, cellular data	Traffic simulation, regression model	Traffic Analysis Zone (TAZ)	No	O_3	NO_2, CO, SO_2, PM_{10}, $PM_{2.5}$	Temporal, spatial
Dias et al. (2016)	LEZ	OD-matrices	TREM mesoscopic emissions model, traffic simulation	(administrative) Type of study areas	VKT, Speed	No	PM_{10}, NO_2, NO_x	Temporal, spatial
Host et al. (2020)	LEZ	Traffic pressure values based on assumptions on population censuses and job distribution	COPERT emission factors	Different zonal levels inside the city	No	No	NO_2, $PM_{2.5}$	Spatial
André et al. (2018)	LEZ	Mobility survey, video monitoring for traffic flows and vehicle speeds	COPERT emission factors	(administrative) Type of study areas	VKT, fuel consumption	CO_2	NO_x, CO, PM_{10}	Spatial
Yin et al. (2023)	DRP	Survey, population synthesis	Eqasim	(administrative) Type of study areas	VKT, travel time	CO_2	NO_x, SO_2, $PM_{2.5}$	Spatial
Ferreira et al. (2015)	LEZ	Air quality data from the air quality monitoring station, traffic count data	Statistical models	Two monitoring stations	No	No	NO_2, PM_{10}	Temporal, spatial
Sun et al. (2022)	Heavy vehicle DRP	Site data from National Weather Service, Statistical Yearbooks	Regression model	Different cities within China	Congestion delay	No	NO_x, CO, SO_2, $PM_{2.5}$	Temporal
Meng (2022)	DRP	Site data from China National Environmental Monitoring Center	Regression model	Different cities within China	No	O_3	NO_2, SO_2, CO, PM_{10}	Temporal
Pu et al. (2015)	LDRP	Vehicle distribution, fuel data, meteorology data	Emission model, traffic simulation (VISUM)	Road class	VKT	CO_2	NO_x, CO, $PM_{2.5}$, HC	Spatial
Qin et al. (2023)	LDRP	Site data from China National Environmental Monitoring Center	Regression model (DID model)	Different zonal levels inside the city	No	No	NO_2, CO, $PM_{2.5}$, PM_{10}	Temporal, spatial
Chen et al. (2023a)	DRP	China Statistical Yearbook, China Vehicle Emission Control Annual Report	System dynamics model, dynamic simulation	Beijing	Parking space tension, fuel consumption	CO_2	$PM_{2.5}$	Temporal
Yi et al. (2022)	DRP	Literature review	Logit regression model	Different cities within China	No	No	$PM_{2.5}$	Temporal
Xiao et al. (2019)	DRP, eliminating old cars	Surveys, interviews, site data from monitoring stations released by Beijing Municipal Environmental Monitoring Center	Multivariate linear regression model	Different road types in Beijing	Speed, traffic volume	O_3	NO_x, CO, $PM_{2.5}$, PM_{10}, HC	Temporal, spatial
Lu et al. (2022)	DRP	Site data from monitoring stations	Regression model	Shanghai	No	O_3	NO_x, NO_2, NO, SO_2, CO, $PM_{2.5}$, PM_{10}	Temporal
This research	DRZ	Open data (nation-wide census of Germany, BASt and local traffic counts)	MATSim	Agent group, local area	Travel time, travel distance, traffic volume, fuel consumption	CO_2, CH_4, and N_2O	CO, NO_x, NO_2, SO_2, $PM_{2.5}$, NH_3, HC, PN, Pb, NMHC, BC, etc.	Temporal, spatial

Note: LEZ: Low Emission Zone; DRP: driving restriction policy; LDRP: license plate driving restriction policy; DRZ: driving restriction zone policy.

- **RG5: Heavy data dependency in data analytic approaches**
  Since gathering data and insights through a trial-and-error approach across different policy scenarios to tailor policy measures is clearly unfeasible, most research on the impacts of LEZ policies heavily depends on either site data analysis or economic equilibrium models (Ricci et al., 2017; Wang et al., 2014), especially utilized regression models based on site data to assess the impacts of DRZ implementation (Gundlacha et al., 2018; Malina and Scheffler, 2015; Wang et al., 2014). For example, Wang et al. (2014) employed a nested logit model to determine the extent to driving limitations may alter the transportation preferences of car proprietors and Malina and Scheffler (2015) proposed a regression model to demonstrate the considerable effect of implementing LEZs in German cities on reducing PM_{10}. This leads to a prevalent issue in most studies is insufficient data. Given that the challenges and costs in gathering detailed site data impede evidence-based policymaking throughout the development of the above sustainable transport policies, necessitating simulation-based policy assessments to address this shortfall.
- **RG6: Emission derived from coarse traffic models in simulation based approaches**
  Only a limited number of studies, such as those by Dias et al. (2016) and Poulhès and Proulhac (2021), have applied simulation-based models for evaluating DRZ or LEZ. These studies typically employ an emission dispersion model derived from aggregated traffic states obtained from macroscopic transportation models (André et al., 2017; Poulhès and Proulhac, 2021; Yin et al., 2018), like trip-based models, to only coarsely predict air quality changes following LEZ implementation. Consequently, these studies fail to assess the implications of activity alterations (e.g., change in duration, time, and location of activities) caused by new policies.
- **RG7: Emission analysis for emission contributing groups**
  Unlike (Dias et al., 2016), who overlooked the impact on diverse demographic groups, Poulhès and Proulhac (2021) examined mainly the effects on local air pollution like NO_2 emissions for different demographics but neglected the emission-contributing segments of the population.
- **RG8: Limited analytical perspective**
  A limited number of studies have assessed policies against all the listed multiple key performance indicators (KPIs), and only a few have examined the spatial distribution changes in perceived emissions.

In summary, existing research inadequately evaluates LEZ and DRP from various perspectives, with simulation-based methodologies predominantly employing macroscopic trip-based models, which are incapable of capturing change in activities and analyzing emissions at a detailed level, specifically regarding the local spatial impact of perceived emissions and emissions from specific demographic groups or subsets of the population affected by policies, with data-driven methods heavily depending on data quantity and quality.

Building upon existing literature, this research makes several key contributions towards addressing identified research gaps RG1, RG2, and RG5 - RG8, while RG3 and RG4 remain open for future research:

- **Innovative Policy Adaptation**: Introduces the concept of Driving Restriction Zones (DRZ) as a targeted adaptation of LEZ and DRP principles but with less restriction and for smaller residential areas. This approach demonstrates the feasibility of achieving significant environmental benefits through spatially focused interventions while alleviating local disruptions commonly associated with broader restriction implementations.
- **New Evaluation Approach**: Proposes a simulation-based evaluation approach for driving restriction policies that transcends traditional methodological limitations by overcoming constraints of macroscopic trip-based models and economic equilibrium approaches through enabling detailed modeling of individual interactions. This granular modeling capability facilitates multi-scale evaluation across global, local, and agent-group levels, providing valuable insights into policy impacts.
- **Integrated Impact Assessment Framework**: Establishes a systematic framework for quantitative policy evaluation through multi-scenario analysis of population-segment-level impacts, environmental externalities, and network efficiency. The framework enables ex-ante assessment and evidence-based refinement of the proposed policy interventions through comprehensive evaluation of mobility patterns, emission profiles.

This research thus provides a framework for evaluating and implementing sustainable transport policies, particularly in this case, driving restriction zones. The methodology enables a comprehensive analysis at multiple levels of aggregation, facilitating the ex-ante assessment and refinement of sustainable transportation measures during their design phase. This comprehensive approach provides valuable insights for designing and implementing evidence-based policies that promote sustainable urban mobility, reduce greenhouse gas emissions, and improve air quality, ultimately contributing to more livable cities.

This section delineates the research lacunae within the domain of this research. The structure for the rest of the research unfolds thus: Section 2 introduces the methodology, which includes an overview of the proposed framework and its operationalization through pertinent configurations for the selected simulator. Section 3 details the design of a case study conducted in Berlin, incorporating the designed DRZ policies for the experiments. Section 4 methodically presents and analyzes the comparison outcomes from various perspectives and levels, discusses the model's accuracy and future outlooks. Section 5 outlines the assumptions and limitations of the research, offers policy insights, and concludes the research.

2. Methodology

2.1. Assessment framework

Fig. 1 illustrates the flowchart of a multimodal agent and activity-based framework for mobility and environmental externalities assessment of DRZ policies. The proposed framework offers several advantages. Firstly, this method facilitates detailed calculations of pollutants, greenhouse gases (GHGs), at the link, individual, and agent group levels. Secondly, it supports heat maps that visualize emissions levels for comparative analysis. Thirdly, it simulates the effects of DRZ on both directly and indirectly affected trips and activities of agents, assessing the corresponding policy implications, in contrast to the trip-based framework that focused only on single-trip impacts (Lu et al., 2023). The simulators employed in the proposed framework outperform both the SUMO simulator and conventional macroscopic simulators, such as PTV Visum, in several key aspects. First of all, agent-based models such as MATSim (Axhausen et al., 2016) or eqasim (Hörl and Balac, 2021), which are open-source microscopic simulators, enable large-scale, nationwide multimodal transport simulations within feasible computational times. Furthermore, unlike the aforementioned simulators, which require actual datasets to differentiate travel patterns by purpose, the simulator used in this research intrinsically provides this information. Last but not least, this multimodal transport simulator also models modal shift effects (changes in transportation mode choices) in addition to changes in route choices. It captures interactions among agents, like drivers and passengers, and their responses to new policies (i.e., affected agents adapt and even drop the old travel plans in the long run), facilitating a comprehensive understanding of policy impacts for policymakers.

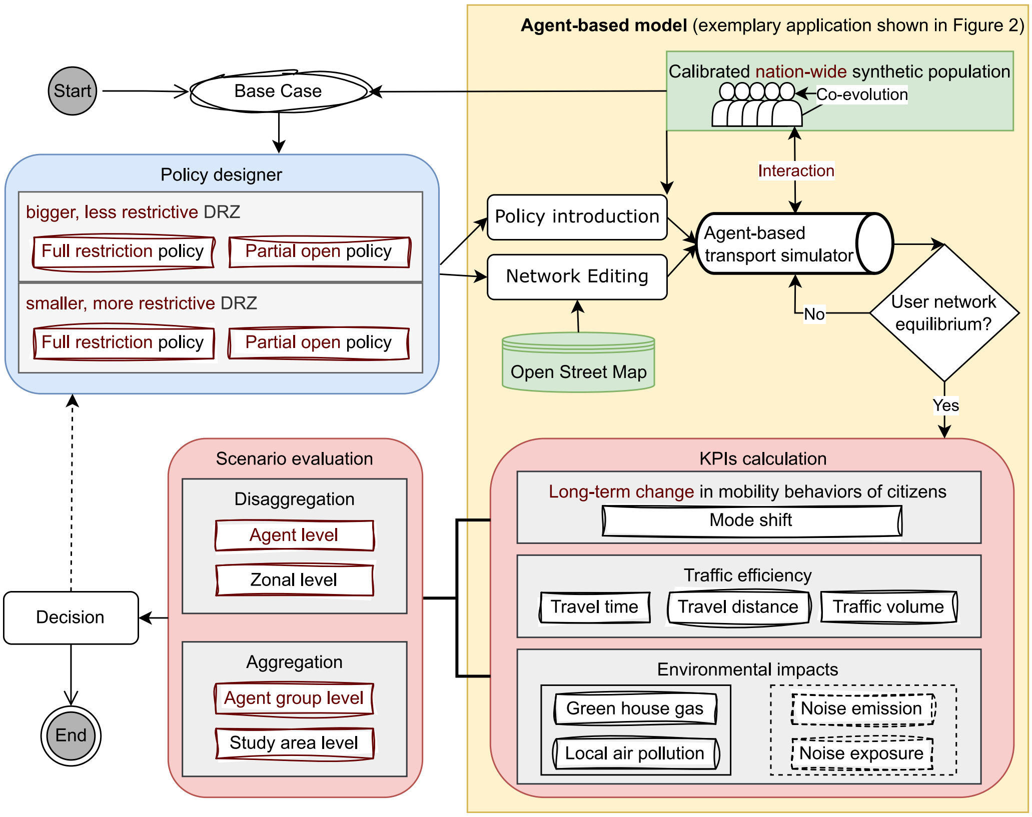


Fig. 1. Framework for assessing DRZ policy impacts through agent-based simulation.

In summary, this agent-based model tracks both short-term (run with fewer iterations) and medium- to long-term (run with more iterations) changes in agents' traffic behaviors, such as alterations in mode, routes, and departure times. After several iterations, simulations converge to achieve user network equilibrium, which is not typically observed in traditional simulators. Overall, the framework is an economical evidence-collection method and apt for evaluating the impacts of driving restriction policies.

2.2. Agent-based model

The proposed framework is applied to various Agent-Based Modeling (ABM) models. Given that MATSim is a leading simulator in the field of ABM (Bastarianto et al., 2023), we have chosen to use it for this research.

MATSim (Multi-Agent Transport Simulation) is an agent-based transport simulation framework designed to model the behavior of individual travelers within a multi-modal transportation system. The goal is to understand and predict the interactions between agents (individuals) and the transportation network to optimize and plan transport systems better. In detail, it is a freely available platform that can model the daily routines of travel and activity for individuals within extensive region (Axhausen et al., 2016). MATSim employs suitable algorithms for selecting departure times, transportation modes, travel routes, etc., to execute perform dynamic scheduling of activity-oriented demands based on time. The framework iteratively simulates every person' s chosen daily sequence of activities and travel (whether existing or newly generated), where each iteration produces comprehensive records of activity and travel events over time that interact with the transport system. At the end of each iteration, the utility (or score) accumulated from the activities and travels completed by each agent is evaluated (Göhlich et al., 2021). During the "replanning" stage, a subset of agents has the ability to adjust their plans based on predefined choice dimensions. The scores obtained from the experienced plans stored in agents' memory are utilized to select the plan for execution in the next iteration, using the logit model. The simulation ends after the acceptable number of iterations which is set to reach a stochastic user network equilibrium.

To better understand how MATSim works in practice, let us examine its core functional components in detail:

I. **Initialization**: The simulation begins with the definition of the initial state, including network, facility, population with their initial plans, etc.

- **Population**: Agents represent individual travelers, each having at least one plan—a sequence of activities (e.g., home, work, shopping) and legs (e.g., driving, walking) defining the agent's daily schedule.
- **Network**: The transportation network consists of nodes (intersections) and links (road segments), with each link having attributes like length, free-flow speed, capacity, number of lanes (including driving direction), and so on.

II. **Mobility Simulation (MobSim)**: This component simulates the actual movement of agents on the network. Each agent follows its plan, and the system dynamically simulates traffic flow, accounting for interactions between agents and the resulting congestion. Key metrics recorded include travel times, delays, and network performance indicators (e.g., link capacity utilization, average speed, traffic volume, etc.). For a link l with a length L_l and free speed v_l, the free flow travel time $t_{l,\text{free}}$ is calculated as:

$$t_{l,\text{free}} = \frac{L_l}{v_l} \tag{1}$$

However, actual travel time $t_{l,\text{actual}}$ may be higher due to congestion, represented as:

$$t_{l,\text{actual}} = t_{l,\text{free}} + \text{delay} \tag{2}$$

During simulation, agents move through the network, and their interactions (e.g., queuing at intersections) can cause delays. The system adjusts travel times dynamically based on real-time network conditions, simulating realistic traffic patterns.

III. **Scoring**: After the simulation, each agent's plan is evaluated using a utility function, which assigns a score based on travel experiences, reflecting the satisfaction or utility of the plan. The utility function U considers factors like travel time, travel cost:

$$U = \sum_i \Bigg(U_i^{\text{activity}} + (\beta_t \cdot t_i + \beta_{\text{late}} \cdot \max(0, t_a - t_{\text{preferred}}) + \beta_{\text{early}} \cdot \max(0, t_{\text{preferred}} - t_a)) + \beta_c \cdot c_i + \beta_{\text{fuel}} \cdot f_i + \beta_{\text{toll}} \cdot \tau_i \Bigg) \tag{3}$$

where U_i^{activity} is the utility derived from activity i. What follows are the terms representing the disutility (negative utility) from traveling between activities i and $i+1$, specifically:

- $\beta_t \cdot t_i$: Travel Time Disutility, where β_t is the time sensitivity parameter (normally negative), and t_i is the travel time for the leg between activities.
- $\beta_{\text{late}} \cdot \max(0, t_a - t_{\text{preferred}})$: Late Arrival Disutility, where t_a is the arrival time, $t_{\text{preferred}}$ is the preferred arrival time, and β_{late} is the sensitivity parameter for being late (normally negative).
- $\beta_{\text{early}} \cdot \max(0, t_{\text{preferred}} - t_a)$: Early Arrival Disutility, where β_{early} is the sensitivity parameter for being early (normally negative or zero).

The remaining terms are:

- $\beta_c \cdot c_i$: Monetary Cost Disutility, where β_c is the cost sensitivity parameter (normally negative or zero), and c_i is the monetary cost for the leg between activities (e.g., public transportation subscription, parking fee).
- $\beta_{\text{fuel}} \cdot f_i$: Fuel Cost Disutility, where β_{fuel} is the sensitivity parameter for fuel costs (normally negative or zero), and f_i is the fuel cost for the leg.
- $\beta_{\text{toll}} \cdot \tau_i$: Toll Cost Disutility, where β_{toll} is the sensitivity parameter for toll costs (normally negative or zero), and τ_i is the toll cost for the leg.

IV. **Re-planning**: Agents update their plans to improve scores, involving strategies like route choice, time choice, and mode choice. For example, if an agent finds a new route with a lower expected travel time t_{new}:

$$\Delta U = \text{score}_{\text{new}} - \text{score}_{\text{old}} \tag{4}$$

If $\Delta U > 0$, the new route is adopted.

V. **Iterations**: The simulation iterates through mobility simulation, scoring, and re-planning steps until the system reaches an equilibrium where agents' plans stabilize, and no significant improvements in scores are observed.

VI. **Equilibrium and Convergence**: The iterative process aims to reach a Nash Equilibrium, where no agent can improve their score by unilaterally changing their plan:

$$\forall j, \quad \Delta U_j \leq 0 \tag{5}$$

where ΔU_j is the change in utility for agent j if they change their plan unilaterally.

2.3. Integration of MATSim and the emission model

The diagram in Fig. 2 illustrates the exemplary application of the framework proposed in Fig. 1, which integrates the emission model with MATSim. The synthetic population, serves as the main data fed into the MATSim simulation. Additional data include the transportation infrastructure, amenities, transit timetables, and so on. The experienced plans for the scenario where transport policies are introduced generate detailed mobility events, which serve two purposes: mobility performance analysis and traffic emission calculation using the corresponding emission factors. The emissions data, as detailed in the resulting emission event file, are subsequently aggregated over time. This aggregation can be done for each agent, vehicle, or based on specific links or areas.

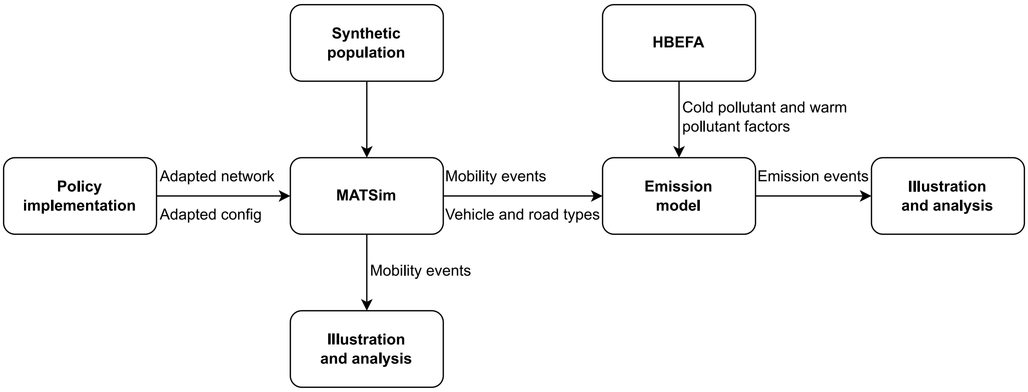


Fig. 2. Application of framework: agent-based model including the emission model.

In deatail, traffic emissions are determined through the MATSim extension of the HBEFA (The Handbook of Emission Factors for Road Transport) emission model (Kickhöfer, 2016) to assess the environmental externalities. The emission model can predict exhaust emissions from motorized vehicles operating on road links, including personal vehicles, buses, and freight carriers with varying fuel consumption and engine sizes, for both cold and warm starts. The emission calculation considers the simulation' s time-dependent traffic situations, road types and characteristics, and the corresponding emission factors in the HBEFA model. In this research, HBEFA version 4.1 is utilized, which is widely accessible across various European nations (Tapia-Dean and Graf, 2019).

Warm emissions are calculated through a two-phase process: (1) gathering traffic data on kinematic characteristics from the mobility simulation of MATSim and (2) merging it with vehicle features (e.g., fuel types, vehicle categories, engine sizes, and the European emission standards) to determine appropriate emission factors from the HBEFA model, based on different types and classes of the road on which the vehicle was driven. The calculation of cold-start emissions also involves two phases: (1) determining the parking duration and the total distance traveled since the simulation starts and (2) integrating this data with vehicle specifics and different types and classes of roads to derive the emission factors. Currently, the HBEFA emission model only accounts for two traffic conditions: free flow and stop-and-go. The emission model calculates the quantities of the following emissions produced by motorized traffic and energy consumption[1]:

- common greenhouse gas emissions, such as CO_2, CH_4, N_2O, and
- air pollutants, such as CO, NO_x, NO_2, SO_2, $PM_{2.5}$, NH_3, HC, Benzene, PN (Particulate Number), Pb (Lead), NMHC (Non-Methane Hydrocarbons), BC (Black Carbon).

In a nutshell, using mobility events from MATSim, the warm or cold-start emissions for each fuel-consuming vehicle on the link can be calculated online or offline at the event time (e.g., when a vehicle exits the link), and then saved as an emission event file for the later analysis.

[1] For more information on the emission modeling in MATSim, refer to Kickhöfer (2016).

2.4. Methodological enhancements for policy evaluation

While this research utilizes existing MATSim components, it makes several methodological contributions through innovative application and integration. The framework's primary contribution lies in establishing a systematic methodology for evaluating driving restriction policies during their design phase. To operationalize this methodology, three key technical modifications were implemented in the standard agent-based model:

1. **Population Segmentation:** Introduction of binary agent classification ("person-internal" for DRZ residents and permitted agents, "person-external" for others) to enable group-specific analysis.
2. **Mode Configuration:** Implementation of a specialized "car-internal" mode with network-wide availability for "person-internal" agents, maintaining identical scoring parameters as the standard car mode to ensure behavioral consistency.
3. **Access Control:** Configuration of differential link permissions where DRZ links accept only "car-internal" mode, while border and traversing roads maintain dual mode access. Public transport and active mode permissions remain unmodified.

These technical modifications enable systematic evaluation of both direct policy impacts on restricted drivers and broader network effects. The integration of group-specific mobility analysis with group-specific emission calculations provides a comprehensive toolset for assessing both transportation and environmental impacts across different population segments. This approach facilitates iterative improvement and fine-tuning of policies before implementation, advancing the field of evidence-based transportation policy design.

3. Experimental design

3.1. The study area

Berlin is the capital and the most populous city in Germany, with a population of approximately 3.7 million in 2019 (Amt für Statistik Berlin-Brandenburg, 2020). The urban area of Berlin covers 891.8 km^2. In this research, we have selected an area for implementing the DRZ policies, based on two main considerations. The first consideration is that this area is densely populated and the zone is located near motorways where high-level traffic emissions exist and affect the people in the study area. The second consideration is that the zone is well-connected to several transit routes, making it comparatively simpler for people impacted by the DRZ policies to use public transport. This location allows us to observe how the DRZ policies influence both motorway and local traffic. It is crucial to recognize that the impacts of the DRZ policies closely depend on the geographic location and the socioeconomic characteristics of the people affected; as Lu et al. (2022) pointed out, these factors can vary significantly across cities. The selected study zone is located to the east of the motorways 'A100' in the western part of central Berlin. Covering an area of approximately 15.6 km^2, the DRZ houses approximately 179,700 residents. Fig. 3(a) shows following three distinct layers:

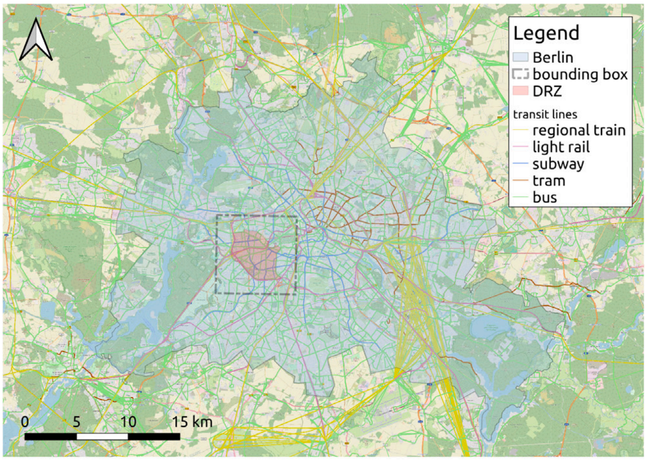
- Driving Restriction Zone,
- the larger local analysis zone (so-called "Bounding Box", a polygon that is tangential to the DRZ area and enlarged by a factor of 2.25), which encompasses DRZ, and
- the administrative area of Berlin.

Examining the study zone in Fig. 3(b), the transportation network is well-developed, with a particular emphasis on rail transit routes. Specifically, the metro line U2 runs adjacent to the top and eastern boundaries of the area, with the U1 line concluding its route within the area from the east. In addition, the metro routes U3, U4, U7, and U9 traverse the area vertically (U7 also crosses the area horizontally), while four of Berlin' s main S-Bahn lines (part of the urban rapid transit system and a type of light rail) and regional trains also run horizontally through the area. Near the western and southern boundaries of the area, a series of S-Bahn stations serve six routes: S41, S42, S45, S46, and S1, S2. Besides, a major train station in the center of the area connects to aforementioned four key S-Bahn routes (S3, S5, S7, and S9) and four regional trains (RE1, RE2, RE7, and RB23), significantly enhancing public transit accessibility. Lastly, numerous green-colored bus lines (are available on almost all traversing roads) supplement the rail transit system, increasing the public transport network's connectivity and ensuring that passengers can reach destinations that are not within walking distance of rail stations. Above that, they help in improving level of service of public transportation system and reducing congestion on popular rail routes during peak hours or in areas with high demand. In summary, the road network within the zone is in excellent condition, with various horizontal and vertical arteries intersecting throughout. This ensures that road users will still have good travel options available after DRZ policies are introduced.

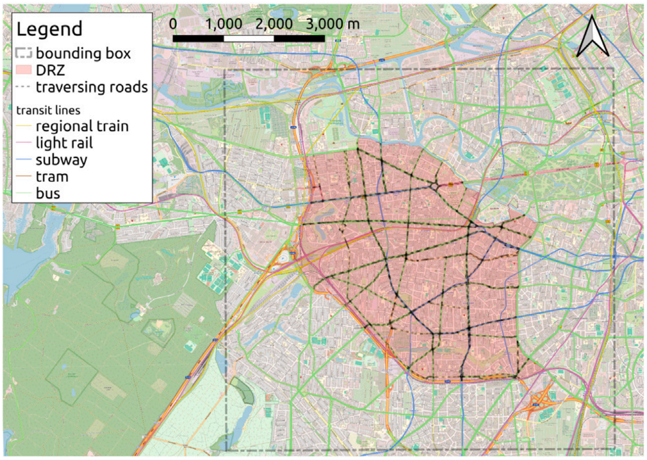
3.2. Design of case studies

To investigate the impact of DRZ precisely, this research established two policies: the first policy involved the depicted traversing roads (presented in dotted lines in Fig. 3) closed, while the second policy entailed opening these roads to allow outside drivers to pass through the zone. It is important to note that the common monitoring area was utilized in both policy cases. In addition, the streets located at the DRZ boundaries are not subject to any limitations, and the DRZ is not an entirely vehicle-restricted area, since residents and allowed outsiders can still operate cars within the area.

To have a less strict DRZ policy for comparison, Policy 2 was introduced as an augmentation to the original DRZ policy. This modification involves reopening certain traversing roads (i.e., primary, secondary, tertiary), permitting restricted outsiders to



(a) Overview of the study area



(b) Zoom-in plot for DRZ scale

Fig. 3. The study area.

traverse the zone, as a way to mitigate the network capacity restriction caused by the DRZ. The network physics, such as topology, number of lanes per link, and road capacity, remained unchanged except for mode permission at roads.

Three scenarios were modeled and evaluated, namely the Base Case, Policy Case 1, and Policy Case 2:

- **Base Case**: without any driving restrictions, derived from the MATSim Open Berlin Scenario available at the GitHub repository.[2]
- **Policy Case 1**: strictly prohibited **one-fifth** of non-local drivers from accessing the DRZ on **one weekday out of every five**, based on the last digit of their license plate (i.e., non-local drivers whose license plates end in two specific digits will be restricted on that day); different groups are restricted on different weekdays; this restriction does not apply to the remaining four-fifths of non-local drivers on that weekday, buses, car riders, light freight deliveries, and local residents.
- **Policy Case 2**: adopted the same settings as Policy Case 1 but allowed outsiders to travel along the arterial routes within the DRZ (presented in dotted lines in Fig. 3(b)).

The detailed configuration of the simulation platform, including mobility simulation parameters, emission calculation specifications, and policy implementation mechanisms, is comprehensively documented in Appendix A. This configuration operationalizes the proposed DRZ policies through carefully calibrated agent-based modeling parameters and systematic emission factor calculations, enabling rigorous quantitative analysis of the policy outcomes presented in the following section.

[2] URL: https://github.com/matsim-scenarios/matsim-berlin. The model calibration details are available in Ziemke et al. (2019).

4. Results

4.1. Overview

This section presents a comparative analysis of different cases to evaluate the impacts of DRZ implementation on both mobility and the environment. The mobility analysis examines individual daily travel patterns, including travel time, distance, and modal shares across different agent groups captured from the Base Case. The environmental assessment investigates spatial distributions of local air pollutants, temporal patterns of greenhouse gas emissions at various geographical scales, and comprehensive impacts on air quality at different aggregation levels. Environmental externalities are also evaluated for specific agent groups to provide a multi-dimensional understanding of policy impacts. Global indicators are analyzed to assess the overall effectiveness of the policy interventions.

To conduct this analysis, agent groups were defined based on their interaction with the DRZ. The captured mobile agents include those who engage in activities within the study zone or operate vehicles at least once in Berlin during the exemplary day in the transport simulation. These agents are classified into the following groups:

- DRZ-related agents, such as residents (those performing home activities inside the DRZ), workers (those performing work activities inside the DRZ), visitors (those performing other activities inside the DRZ), and passers (who drive through the zone but without performing any activities within the zone), and
- DRZ-unrelated agents (the agents unrelated to the DRZ who travel in Berlin, but do not traverse the zone.).

The analysis considers all agents in Berlin to provide a comprehensive understanding of travel behavior impacts. The following sections examine travel behavior patterns among these agent groups (Section 4.2), followed by an assessment of environmental externalities through traffic emissions analysis at both Berlin-wide and local scales, as well as across different agent groups (Sections 4.3 and 4.4). Both policies are then evaluated from a global perspective (Section 4.5). The discussion and case study outcomes are presented in the final two subsections.

4.2. Mobility measurements

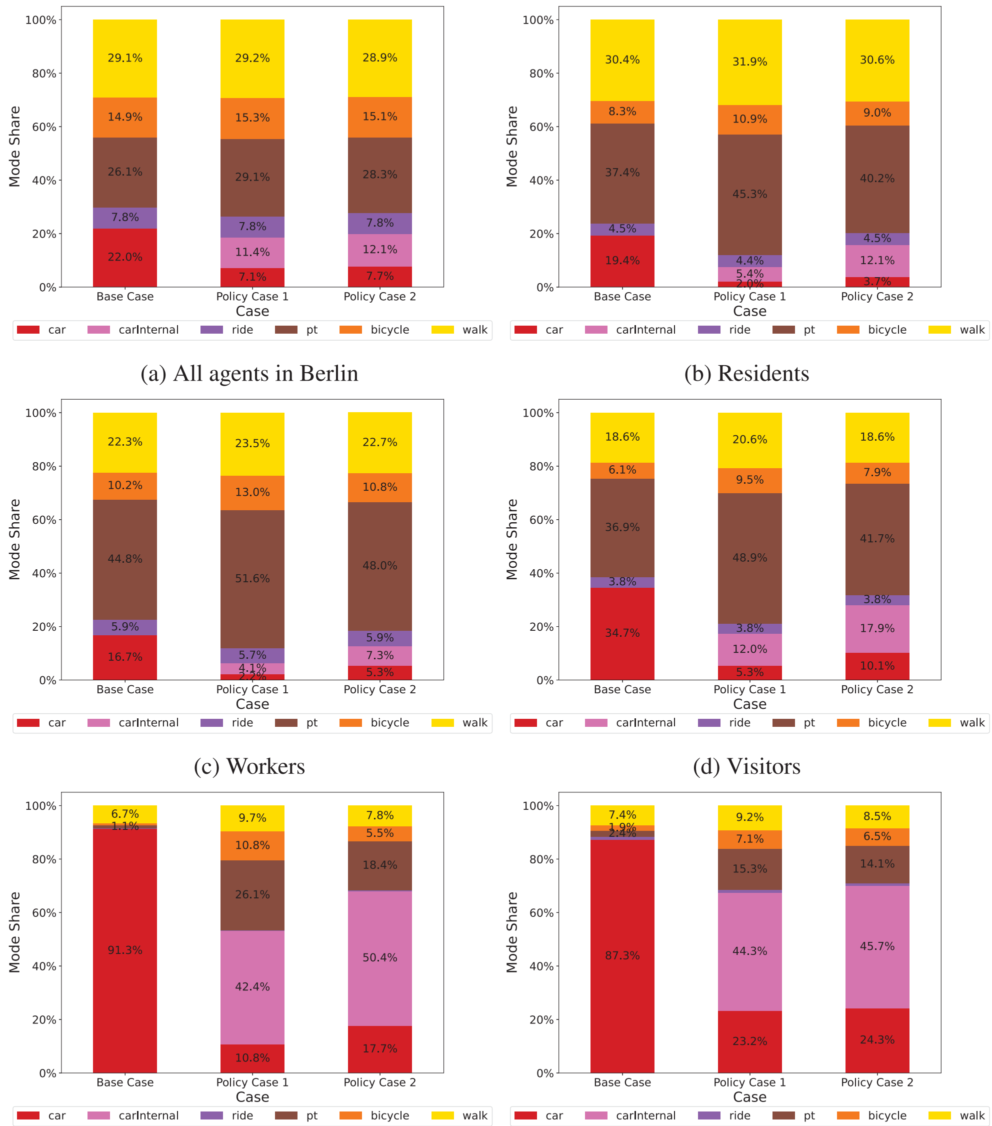
Table 2 provides a summary of the mobility indicators, comparing travel patterns across scenarios. The average individual daily travel time and distance (accumulated by the daily number of trips) in the two DRZ cases are higher than those in the Base Case. The increase in travel time more significant than the relatively constant growth in travel distance. The travel time for all agents in Berlin rises by 6.8% and 5.1% in Policy Case 1 and 2, respectively, whereas their travel distance grows only slightly by 0.9% and 0.4%, respectively. This increase in travel time is likely caused by worsened road congestion and detours taken by car users, as well as less efficient alternative transportation options regarding speed and transfers for active and transit mode users. In addition, longer travel time or distance in the Base Case leads to amplified increases in travel time under the two policies. For instance, among all agent groups, residents, workers, and visitors experience relatively smaller increases in travel time while other car-captured agents have larger increases, with passing drivers experiencing a 32.9% increase and DRZ-unrelated drivers a 21.9% increase in Policy Case 1. The reason behind is that these two car-captured agent groups travel with daily travel distances exceeding 40 km.

Table 2
Comparative analysis of average daily travel duration (TT, in minutes) and travel distance (TD, in kilometers) for various agent groups.

Agent groups		Base case		Policy Case 1		Policy Case 2	
		TT	TD	TT	TD	TT	TD
All agents in Berlin		99.8	26.0	106.6 (+6.8%)	26.3 (+0.9%)	104.9 (+5.1%)	26.1 (+0.4%)
Captured agents[a]		125.4	42.0	153.0 (+22.0%)	42.4 (+0.9%)	147.4 (+17.6%)	42.0 (+0.0%)
DRZ-unrelated agents		127.0	44.7	154.8 (+21.9%)	44.8 (+0.3%)	151.6 (+19.4%)	44.6 (−0.1%)
DRZ-related agents	Residents	93.0	22.8	110.7 (+19.0%)	23.7 (+3.7%)	99.0 (+6.4%)	23.0 (+0.7%)
	Workers	101.7	25.4	117.4 (+15.4%)	26.0 (+2.3%)	107.2 (+5.4%)	25.5 (+0.2%)
	Visitors	137.3	34.0	164.0 (+19.4%)	35.0 (+2.9%)	146.9 (+7.0%)	34.2 (+0.7%)
	Passers	147.7	48.0	196.3 (+32.9%)	50.1 (+4.4%)	177.4 (+20.1%)	48.3 (+0.7%)

Note:
[a] Captured agents include DRZ-related agents and DRZ-unrelated agents.

Notably, compared to Policy Case 1, Policy Case 2 achieves both shorter travel times for residents, workers, and visitors, and reduced travel distances for passing drivers. This can be explained by the fact that Policy Case 2, which allows traversing roads in the DRZ, reduces not only travel distance due to less detours but also congestion on the peripheral roads. As for the overall outcomes in Berlin, the substantial increase in travel duration could be attributed to a greater shift from private cars towards active



(a) All agents in Berlin (b) Residents

(c) Workers (d) Visitors

(e) Passing drivers (f) DRZ-unrelated drivers

Fig. 4. Modal share by agent groups.

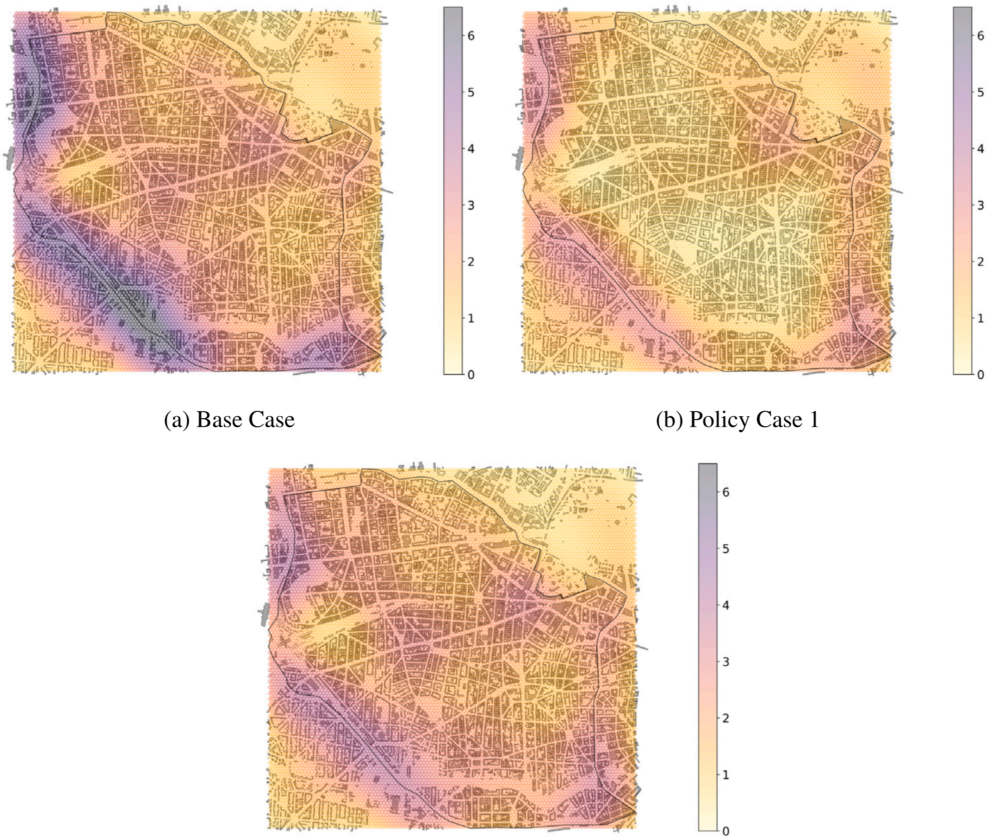
transportation modes, which typically have lower speeds (for more information, see Fig. 4(a)). It is also worth knowing that DRZ policies have a lesser impact on the travel time of DRZ-related agents and less on the travel distance of DRZ-unrelated agents. Nevertheless, the proposed Policy 2 will not significantly hinder individual travel.

Having examined the changes in travel time and distance, we now turn to analyzing how these changes are reflected in travelers' mode choices, as modal shifts can help explain the observed variations in travel patterns. Fig. 4, displays the modal shares of trip counts by agent groups for each simulation scenario. Specifically, Fig. 4(a) depicts the modal shares of all agents' trips in Berlin. The results indicate that the proportion of individual automobile trips (i.e., car and car-internal trips) diminishes by 3.5% and 2.2% in Policy Case 1 and 2, respectively. It is noteworthy that a considerable proportion of car trips has been shifted to public transportation, with an increase of 3% in Policy Case 1 and 2.2% in Policy Case 2. To examine the impact of the DRZ on the shift from car usage, this research analyzes the modal shares of car-captured agents, as shown in Figs. 4(e) and 4(f). In Fig. 4(e), the proportion of passing drivers who starts to use public transportation and bicycle increased by from 23.2%–38.1%, while in Fig. 4(f), the DRZ-unrelated drivers decreased by approximately 20%. Of those, 15% and 13% of car trips were respectively redirected to public transit. This impact is even more pronounced observed in Policy Case 1.

The modal shares of residents, workers, and visitors are discussed in Figs. 4(b), 4(c), and 4(d), respectively. Unlike the findings in Figs. 4(a), 4(e), and 4(f), the three DRZ-related agent groups show a smaller reduction in car usage in Policy Case 2 compared to Policy Case 1. This is because the DRZ' s crossing roads are accessible for those to drive through the area and are, therefore, heavily occupied. Fig. 4(b) illustrates that local residents reduce their number of car-internal trips in Policy Case 1 and 2 by different magnitude, corresponding to decreases of 12% and 3.6%, respectively. The possible reason for this is the deteriorated road network condition on peripheral areas of the DRZ in the Policy Case 1. Furthermore, Policy 2 with open traversing roads still has same level of car use, so the workers and visitors are not as much affected as they are in Policy Case 1, as shown in Fig. 4(c) and in Fig. 4(d). In addition, this research discovered that the reduced ratios of car trips for the agents in Berlin (Fig. 4(a)) under the two DRZ policies are significantly smaller compared to those for other agent groups. This phenomenon is known as the rebound effect, where enhanced traffic conditions result in a rise in new private automobile users (Coulombel et al., 2019; Yin et al., 2018).

4.3. Environmental externalities

Fig. 5 illustrates the NO_x emission levels during the morning peak hour, specifically from 8 to 9 a.m. Policy 1 achieves better local air pollution reduction effects. Conversely, Policy 2 has slightly less impacts, but still enhances the livability of nearly all zones within the study area (especially at the east and south border of DRZ) through a marked decrease in NO_2 emissions. However, its effect on emission reduction in the center of DRZ is not as pronounced as that of Policy 1. The reason for that is Policy Case 1 does not open the traversing roads within DRZ and thus, the affected agents changed the driving routes due to deteriorated driven conditions.



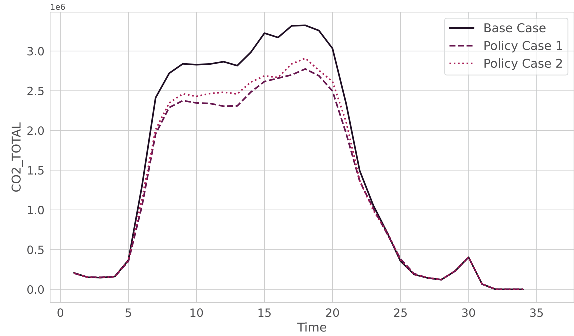
(a) Base Case

(b) Policy Case 1

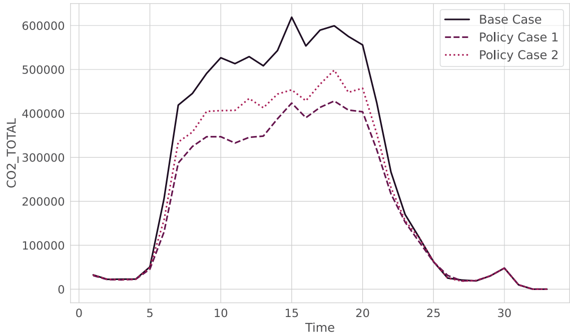
(c) Policy Case 2

Fig. 5. Spatial local air pollution (NO_x) distributions for different scenarios (unit: 0.1 kg).

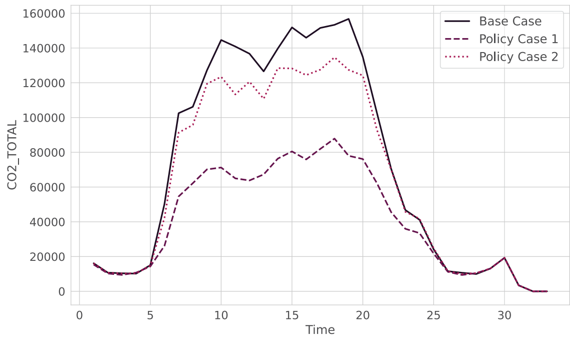
To better understand the temporal dynamics of these emission patterns, we analyzed the CO_2 emissions throughout the day. Fig. 6 illustrates the hourly CO_2 emissions across three different areas: Berlin (a), Bounding box (b), and DRZ (c) by the three cases. As shown in three subfigures, the results indicate that both policy cases have noticeable reductions in CO_2 emissions from 07:30 to 20:00. Specifically, Policy Case 1 and Policy Case 2 demonstrate a noticeable decline in emissions during peak hours, particularly around the morning and evening rush hours. This trend is consistent across all three areas, suggesting that driving restriction policies are effective in reducing overall CO_2 emissions. In terms of the emission reduction effects, Policy 1 performs better in the DRZ area, while Policy 2 does better in the Bounding box area. As expected, Policy Case 2 performs better in Bounding Box area than DRZ because of loose road access restrictions. This evidence supports the implementation of driving restrictions as a viable measure to mitigate urban air pollution and improve environmental health.



(a) Berlin



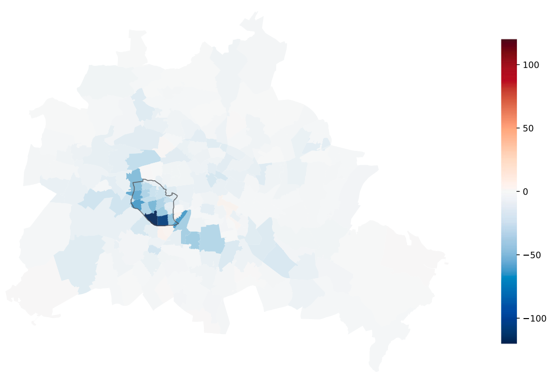
(b) Bounding box



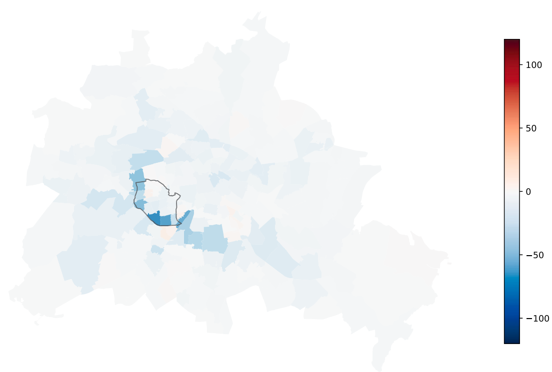
(c) DRZ

Fig. 6. CO_2 emissions (unit: 0.1 kg/h) throughout the day.

While the temporal analysis provides insights into emission patterns throughout the day, it is also crucial to understand the spatial distribution of these changes across the city. Fig. 7 demonstrates the spatial changes in NO_2 emissions in Berlin under two policy scenarios compared to the base case. The results demonstrate a substantial reduction in NO_2 emissions in most zones under both policies, with the darkest blue regions experiencing the greatest decreases. Policy Case 1 shows a pronounced reduction in NO_2 emissions particularly concentrated in the central and southwestern parts of the city. In contrast, Policy Case 2 exhibits a more widespread reduction across various zones, with less intensity in the central region compared to Policy Case 1 (due to less mode shift to active modes and less detours). Furthermore, a notable trend indicates that both policies reduces local air pollutants along surrounding major roads such as 'A100'. This outcome can be attributed to secondary effects of the DRZ, including changes in driving routes and modes of transportation, which lead to reduced NO_2 concentrations in specific areas.



(a) Change in zonal pollutant (NO_2) emission from the Base Case to Policy Case 1.



(b) Change in zonal pollutant (NO_2) emission from the Base Case to Policy Case 2.

Fig. 7. Change in zonal pollutant (NO_2) emission (unit: 0.1 kg/m^2).

Table 3
Greenhouse gas emissions and local air pollutants.

	Base case	Policy Case 1	Policy Case 2
	Berlin		
CO_2 (kg)	5,108,791.4	4,300,706.8 (−15.82%)	4,463,505.3 (−12.63%)
NO_x (kg)	10,460.4	8776.1 (−16.1%)	9121.1 (−12.8%)
SO_2 (kg)	24.9	21.0 (−15.78%)	21.8 (−12.6%)
PM_{10} (kg)	396.4	316.1 (−20.26%)	328.8 (−17.05%)
	Berlin-bounding box		
CO_2 (kg)	4,206,839.2	3,653,339.6 (−13.16%)	3,730,340.3 (−11.33%)
NO_x (kg)	8634.5	7463.9 (−13.56%)	7625.4 (−11.69%)
SO_2 (kg)	20.5	17.8 (−13.12%)	18.2 (−11.3%)
PM_{10} (kg)	312.7	259.4 (−17.06%)	265.9 (−14.97%)
	Bounding box		
CO_2 (kg)	901,952.1	647,367.2 (−28.23%)	733,165.1 (−18.71%)
NO_x (kg)	1825.9	1312.2 (−28.13%)	1495.7 (−18.08%)
SO_2 (kg)	4.4	3.2 (−28.16%)	3.6 (−18.67%)
PM_{10} (kg)	83.6	56.7 (−32.25%)	62.9 (−24.84%)
	Bounding box-driving restriction zone		
CO_2 (kg)	663,493.7	511,058.1 (−22.97%)	521,426.7 (−21.41%)
NO_x (kg)	1340.4	1053.3 (−21.42%)	1067.1 (−20.39%)
SO_2 (kg)	3.2	2.5 (−22.93%)	2.5 (−21.39%)
PM_{10} (kg)	66.3	47.0 (−29.12%)	48.1 (−27.4%)
	Driving restriction zone		
CO_2 (kg)	238,458.4	136,309.1 (−42.84%)	211,738.4 (−11.21%)
NO_x (kg)	485.5	259.0 (−46.66%)	428.7 (−11.7%)
SO_2 (kg)	1.2	0.7 (−42.69%)	1.0 (−11.1%)
PM_{10} (kg)	17.4	9.7 (−44.17%)	14.8 (−15.1%)

To quantify the environmental impacts more precisely, Table 3 summarizes the daily amounts of CO_2 emissions and air pollutants such as NO_x, SO_2, and PM_{10}. All emission results presented in this research are upscaled based on simulations with a 1% population. According to global emission measurements in Berlin, the two policies reduced emissions by approximately 16% in Policy Case 1 and 13% in Policy Case 2, compared to the Base Case. As shown in Fig. 4(a), the modal shift ratio for cars was calculated as 15.9% (3.5% of 22%) in Policy Case 1, and 10% (2.2% of 22%) in Policy Case 2. These significant ratios are the main reason for the notable emission reductions, with Policy Case 1 achieving greater reductions due to a larger shift from car usage.

Looking at the spatial distribution of these reductions, when estimating pollutants in the Berlin area without a bounding box, the two policy cases achieved further emission reductions of approximately 11%–17%, with Policy Case 1 showing a slightly greater reduction. The analysis area of the bounding box includes the DRZ and adjacent regions, ensuring an accurate representation of the local effect. Due to stringent measures, Policy Case 1 resulted in a significant reduction of emissions within the DRZ area, with reductions double those in the DRZ periphery and about four times greater than those observed in Policy Case 2, culminating in a 43%–47% decrease compared to the Base Case. Meanwhile, the reductions in Policy Case 2 remained of a comparable magnitude, though its trend for different pollutants contradicted the trend observed under the full restriction policy, with more reduction in the DRZ peripheries and the bounding box and less in the DRZ area. The fourfold increase in emission reduction in Policy Case 2 is clearly due to the restriction of four times as many agents, while similar mobility impacts on the DRZ periphery area by both policies result in the same level of emission reduction. It is also important to note that the reduction percentages might vary based on the scale of the analysis area.

4.4. Agent group level evaluation

Poulhès and Proulhac (2021) developed emission models based on national survey data to evaluate NO_2 emissions under various policies with differing degrees of restriction. This study, however, suffers from a lack of granularity in its approach to modeling the impacts of these policies, as it does not incorporate network modeling. Consequently, this may lead to inaccurate results. Additionally, Poulhès and Proulhac (2021), along with other existing studies, does not track emissions from vehicles specific to individual agent groups. Such tracking is vital for evaluating the effectiveness of DRZ. To address this gap, a new feature has been developed for the MATSim emission extension, enabling emission calculation at the agent group level, based on classified agents and their trip purposes.

Using the developed analyzer, Table 4 presents a comprehensive analysis of emission changes across agent groups under both policy scenarios. The analysis reveals several key patterns in the distribution and magnitude of emission reductions:

- **Distribution of Impact:** Non-affected agents (those not directly affected by the proposed policies) contribute the largest share to total emission reductions (approximately 86%–89% for both CO_2 and $PM_{2.5}$). This is due to their dominant proportion in the total population and smoother traffic in surrounding areas, as well as their significant mode shift. Passers contribute the next largest share (6.7–7.7%). This pattern remains consistent across both pollutant types and policy scenarios, suggesting stable behavioral responses to the interventions.

- **Effectiveness by Agent Group:** Workers demonstrate the highest percentage reduction in emissions under Policy Case 1 (63.1% for CO_2, 63.6% for $PM_{2.5}$), while residents show consistent high reductions across both policies (54.9–59.3% for CO_2). These substantial reductions indicate the policies' effectiveness in modifying travel behavior among DRZ-related agents.
- **Policy Comparison:** Policy Case 1 achieves higher total emission reductions (39.5% for CO_2, 39.3% for $PM_{2.5}$) compared to Policy Case 2 (37.9% for CO_2, 37.8% for $PM_{2.5}$). However, the relative contribution patterns remain similar across both policies, suggesting consistent underlying behavioral mechanisms.

Table 4
Analysis of emission changes by agent groups under different policy scenarios.

Agent type	Policy Case 1		Policy Case 2	
	Reduction from Base Case	Share (%)	Reduction from Base Case	Share (%)
CO_2 changes				
Residents	−259,593.5 kg (−59.3%)	1.9%	−240,192.2 kg (−54.9%)	1.7%
Workers	−114,130.5 kg (−63.1%)	0.8%	−70,852.0 kg (−39.1%)	0.5%
Visitors	−435,533.1 kg (−56.0%)	3.2%	−304,337.0 kg (−39.1%)	2.2%
Passers	−1,068,883.9 kg (−44.8%)	7.7%	−928,108.1 kg (−38.9%)	6.7%
Non-affected agents	−12,058,492.6 kg (−38.2%)	86.4%	−11,828,453.4 kg (−37.5%)	88.9%
Total change	−13,936,633.6 kg (−39.5%)	100%	−13,371,942.7 kg (−37.9%)	100%
$PM_{2.5}$ changes				
Residents	−5.5 kg (−57.3%)	1.9%	−5.4 kg (−56.2%)	1.9%
Workers	−2.4 kg (−63.6%)	0.8%	−1.5 kg (−39.2%)	0.5%
Visitors	−9.0 kg (−55.2%)	3.0%	−6.3 kg (−38.6%)	2.2%
Passers	−22.1 kg (−44.6%)	7.4%	−19.2 kg (−38.7%)	6.7%
Non-affected agents	−258.1 kg (−38.1%)	86.9%	−253.4 kg (−37.4%)	88.7%
Total change	−297.1 kg (−39.3%)	100%	−285.8 kg (−37.8%)	100%

Note: Values in parentheses show the reduction rate, i.e., percentage reduction from Base Case.

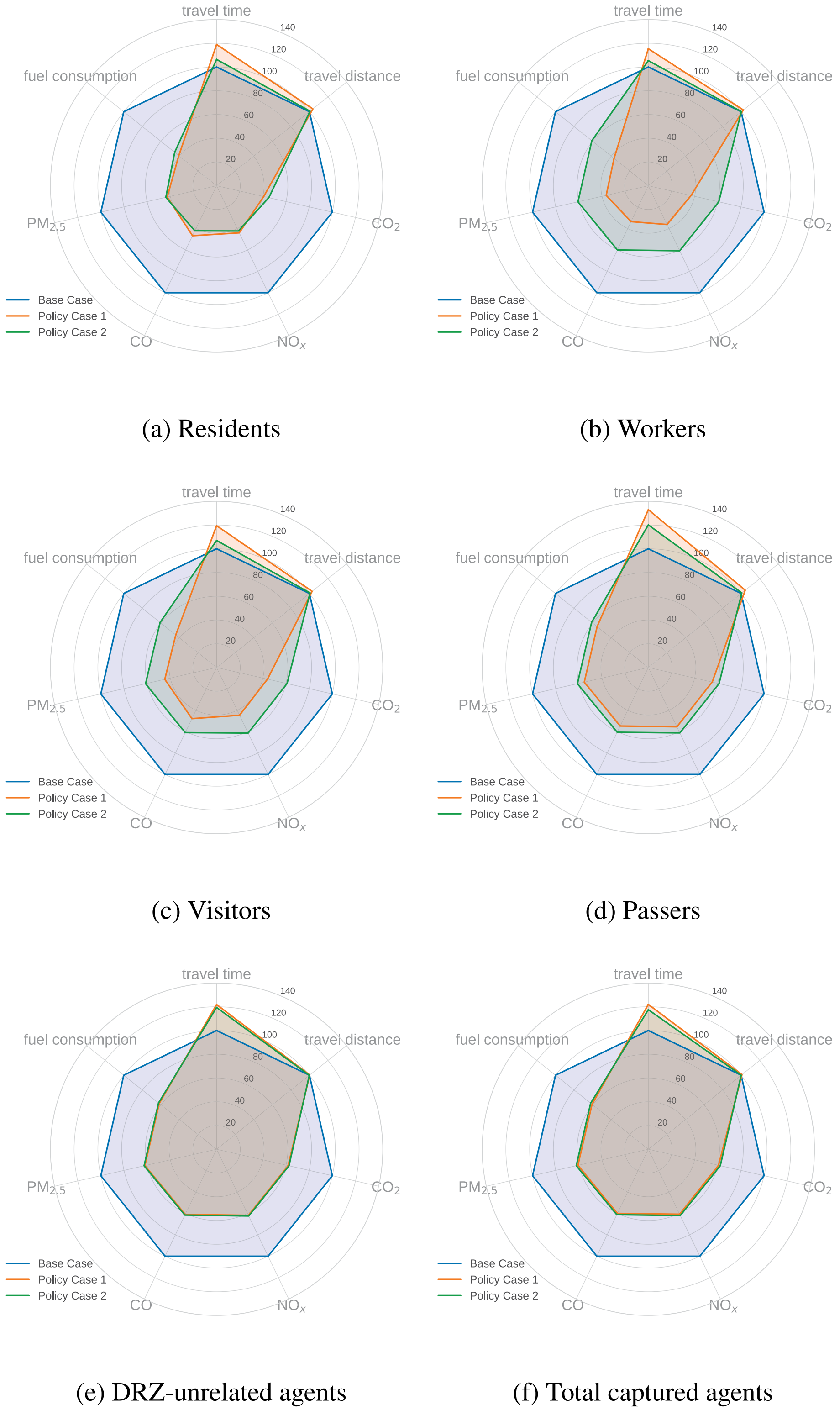
Fig. 8 illustrates the impact of DRZ policies on three key metrics by different agent groups: transport efficiency, environmental impact, and resource consumption. The data indicate a general decrease in fuel consumption, greenhouse gases (GHG) emission and local air pollution across all groups. This improvement, however, is accompanied by a minor decline in traffic efficiency for residents, workers, and visitors and a more pronounced decrease for passers and agents not related to the DRZ. The reduction in GHG, local air pollution, and fuel consumption appears consistent among most agent groups for both policy scenarios. Notably, Policy 1 is more effective in reducing emissions for workers and visitors because of mode shift towards public transportation and bicycle. Furthermore, passers seem to contribute less emissions in the Policy Case 1 but experience much more travel time due to shift towards slow modes. Last but not least, the DRZ policy, which restricts one-fifth of agents while permitting access to the remaining four-fifths in Policy Case 2 still leads to around 40% emission reduction from agent groups workers, visitors and passers. The main contributions are the better traffic conditions and mode shifts caused by the proposed policy.

4.5. Global evaluation

Based on a comprehensive evaluation of our results, analysis of Figs. 9(a) and 9(b) reveals that both policies yield positive environmental impacts in their respective areas, albeit with a minor compromise in transportation efficiency (i.e., a slight increase in travel time and distance). The illustration in Fig. 9(b) notably highlights a significant enhancement in local air quality and decreased greenhouse gas emissions within DRZ. Overall, DRZ restriction applied for one-fifth of the agents results in an approximate 20% emission reductions due to emissions from buses almost constant. In detail, Policy Case 1 performs better regarding emission reduction but worse regarding mobility efficiency. Additionally, Policy 2 facilitates smoother traffic flow by allowing transit traffic in the DRZ and its surrounding areas.

4.6. Validation and discussion

Regarding the mobility impacts of DRZ, we noted that the daily travel time across some agent groups experiences a more pronounced increase compared to the daily travel distance. Although the influence on the traveled distance was insignificant in our research, detours may occur in other cases due to low-level network connections and a high-level routing reliance on the restriction area. The rise in travel duration can be attributed to two factors based on the illustration of simulation results. The first reason could be the increased traffic volume on the traversing roads (Policy Case 2), coupled with localized traffic congestion near the area (Policy Case 2). This highlights the need for targeted interventions like pull measures to encourage these individuals to reduce their car usage. Additionally, certain car users switch to less time-efficient transportation modes, such as walking or cycling, with lower speeds or requiring additional time costs for transit interchanges (refer to the modal shift in Fig. 4). Furthermore, since 200 iterations were configured in our simulation, the cumulative changes in agent' s travel pattern are thus anticipated to manifest

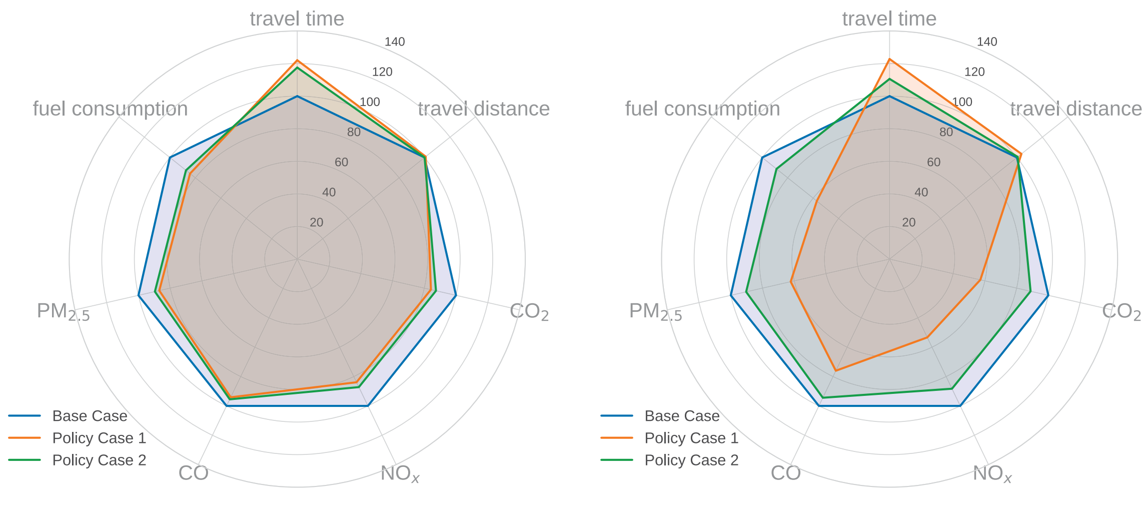


(a) Residents (b) Workers

(c) Visitors (d) Passers

(e) DRZ-unrelated agents (f) Total captured agents

Fig. 8. System metrics by agent groups.



(a) Berlin-wide metrics comparison (b) DRZ-wide metrics comparison

Fig. 9. Overall performance for the study area Berlin and DRZ.

over six months after the policy' s introduction. Consequently, in Berlin, the DRZ policies led to an approximately 3.5% mode shift from cars towards green transportation modes out of a total of 22% (Fig. 4a), which appears to be a significant modal shift. It is reasonable to expect that simulations with fewer iterations would result in less modal shift, leading to a relatively shorter-term impact (Zhuge et al., 2019).

In terms of environmental impacts, the accuracy of the calculated emissions in the Base Case should be discussed firstly. For data acquisition and validation of the utilized mobility model, please refer to Appendix B. For the validation of the emission model, several studies have employed the MATSim emission extension to simulate emissions across various scenarios (Hülsmann et al., 2014, 2011; Kickhöfer and Kern, 2015; Lejri et al., 2018; Mastio et al., 2023; Bell et al., 2023; Axhausen et al., 2016). Furthermore, according to the Berlin official air quality plan 2015, NO_x emissions from all vehicle categories totaled 5817 tons per year, with cars contributing approximately 55% (Senate Department for the Environment Transport and Climate Protection of Berlin, 2019). This equates to 8.7 tons per day. The upscaled (i.e., for the scenario with 100% population) simulated NO_x emissions (excluding those from public transportation vehicles) amount to approximately 7.4 tons per day in the base case scenario, which is underestimated by 14.9%. This is mainly due to the underestimated simulated sample of mobile population, which is approximately 2.65 million and about 17.9% less than the real mobile population in 2015 (approximately 3.47 million × 0. 93[3] = 3.23 million). Lastly, the results are compared with other papers in the field. The comparison reveals that the outcomes of this research are consistent with those of other policies, displaying a similar magnitude. Detailed comparisons can be found in Table C.1, which is included in Appendix C for further reference. Nevertheless, based on the compelling simulation results, the research determined that the DRZ policies resulted in large emission reductions in both city-wide and local levels. The significant reduction in CO_2 emissions can be primarily attributed to a major shift from automobiles to alternative transportation options, particularly mass transit, facilitated by the dense network of transit lines in the research area.

Therefore, further investigation is needed to assess the effectiveness of the policy in conjunction with other transportation alternatives. This investigation could include e.g., Park-and-Ride (P&R), improving transit connections, since Park-and-ride alone has the potential to decrease vehicle numbers and enhance public transport usage, thereby mitigating the adverse effects of automobile usage, as explored in Huang et al. (2019). In addition, future research could further explore the implementation of different restricted areas or policies combined with different traffic control measures. Examples include time-dependent DRZs, policies that adjust based on real-time traffic conditions, or policies combining DRZs with road pricing. Lastly, the implementation of the DRZ policy raises several questions. For instance, what infrastructure and environment are necessary for people to live or engage in activities in a car-free zone without daily restrictions? To ensure the successful implementation of future DRZs, it is crucial for city planners to investigate the territory's hosting (Baehler, 2019) and for social economists to examine the living preferences of the local residents (Gundlacha et al., 2018).

[3] The mobile population ratio in Berlin. Mobilität in Städten – SrV 2018. https://www.berlin.de/sen/uvk/verkehr/verkehrsdaten/zahlen-und-fakten/mobilitaet-in-staedten-srv-2018.

5. Conclusions and policy implications

5.1. Conclusions

This research introduces a agent-based model designed to evaluate driving restriction zone policies. It specifically analyzes the impact of the DRZ policies regarding mobility and environmental externalities in Berlin, providing an practical applied example to illustrate the framework's use. The agent-based simulation is set up to apply two different DRZ strategies: a complete restriction for all roads, and a restriction with only cross-through routes accessible for outsiders. Specifically, both policies decreased car trips in Berlin by more than 3%, but also increased the travel time and distance for agents by approximately 5%–7%, respectively. Changes in mobility patterns varied by agent group. Passing and DRZ-unrelated drivers were more sensitive to the policy, experiencing a 4 times greater increase in travel times compared to the average increase for all agents in Berlin. Moreover, a considerable proportion of car trips have shifted to green transport modes, including public transportation, with 3% in Policy Case 1 and 2.2% in Policy Case 2. Regarding environmental factors, the two designed policies led to a 16% and 13% reduction in CO_2 emissions in Berlin for Policy Case 1 and 2, respectively. The reduction was even greater in the local analysis area (up to 47%). Comparable reduction were noted in air pollutant levels. The designated policy is expected to decrease emissions in surrounding neighborhoods adjacent to main roads, with this effect being more pronounced in Policy 2, where traversing roads remain open. Furthermore, the newly developed feature for the MATSim emission extension also calculates emissions across different agent groups. The findings indicate that the DRZ policies lead to an overall reduction both in GHG emissions and local air pollution for all agent groups (with reductions of around 40–60%; most emission reductions are from non-affected agents and passers in terms of the amount). Policy 1 is particularly effective in minimizing external costs by workers and visitors, while Policy 2 results in lower external costs from residents. Our analysis indicates that policymakers should select a policy based on their specific objectives. Policy Case 1 offers greater environmental benefits, while Policy Case 2 has less negative impacts on transport efficiency.

5.2. Limitations

However, the presented case study has several limitations that must be addressed in future research. Firstly, the simulator MATSim, due to its queue-based traffic flow modeling approach, cannot capture changes in driving behaviors and interactions between pedestrians and drivers. As a result, the associated road safety impacts remain unevaluated. Secondly, improvements are required in the emission calculation methodology, particularly in the following areas. One aspect involves accounting for emissions from rail vehicles, dismissed in the research. The reason for this is railway emissions contribute a mere 0.7% to the total transport sector emissions (Amt für Statistik Berlin-Brandenburg, 2020). Consequently, a mode shift towards public transport of 1.9% in Policy Case 1 and 0.3% in Policy Case 2 corresponds to 0.0133% and 0.0021% of the total transport sector emissions, respectively. Moreover, variations in occupancy levels do not significantly affect emissions from public transport vehicles, due to the low marginal emission factors of these vehicles (Bigazzi, 2019). Another area of improvement is to consider the use of detailed emission factors corresponding to different vehicle fuel types, as per European emission standards, instead of relying on the average HBEFA factors. This will be done when data on detailed vehicle types in the market become available. Thirdly, another notable limitation of this research is the treatment of noise, particularly for EVs. The MATSim noise extension used was primarily designed for conventional vehicles, and without detailed EV distribution data, accurate noise modeling proved challenging. Our preliminary analysis showed marginal noise impacts even when assuming all vehicles were conventional, leading us to exclude noise-related results from the final analysis. Fourthly, DRZ-related agents can utilize micro-mobility transportation options for accessing mass transit to reduce the travel time. For modeling the dynamics of the multi-modality, developing new features for the agent-based model is needed. Lastly, lack of detailed information in the MATSim Berlin Scenario, we could not evaluate the impacts of DRZ on various demographic groups in the case study. However, with other MATSim open scenarios, it is possible to perform such evaluation in the future research.

5.3. Policy implications

The case study conducted in a residential zone in Berlin, Germany, demonstrates the practical application of the proposed framework. The analysis of the DRZ policy's effects on human mobility patterns, transport efficiency, and environmental outcomes, including greenhouse gas emissions, air pollutants, validates the model's effectiveness. Our research highlights the potential implications of DRZ policies in Berlin, serves as a valuable reference for urban planners and policymakers, emphasizing the importance of integrating transport and environmental strategies for sustainable urban mobility. The proposed systematic, simulation-based framework used to conduct the case study and demonstrate the usages for DRZ policies, offering a comprehensive examination of various policy scenarios. With framework extensions and validations in the future research, it may be suitable for evaluating other studies on sustainable transport interventions like low emission zones, superblocks, time-dependent DRZs (Yannis et al., 2006). By thoroughly modeling emissions and accounting for congestion effects, it not only forecasts the anticipated changes in transport system efficiency and quantifies expected emission reductions, thus advancing both efficient urban mobility and environmental sustainability. The evaluation tool achieves this by modeling intricate traffic patterns and computing detailed environmental metrics, even without crucial site data, through the modification of simulation parameters and control algorithms, thereby producing simulated data for various policy scenarios. Therefore, this method represents a flexible and cost-effective way to evaluate benefits and costs of the policies in real-world contexts, facilitating informed decision-making. Furthermore, the primary emphasis of the multiple KPIs-based framework lies in its four-tiered comparison system (global, zonal, local, and particularly among different agent groups). This granularity is invaluable for policy-makers aiming to ensure that the proposed green initiatives are both effective and equitable and meet the diverse needs of different population segments.

CRediT authorship contribution statement

Hao Wu: Writing – original draft, Software, Methodology, Conceptualization. **Danyue Zhi:** Writing – review & editing, Methodology. **Biao Yin:** Writing – original draft, Software, Methodology. **Chengqi Lu:** Software, Methodology. **Liu Liu:** Writing – review & editing. **Constantinos Antoniou:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Experiment configuration

This section delineates the necessary simulation configuration and code development to tailor the standard agent-based model for evaluating the driving restriction policies. It will elaborate on the operationalization of the proposed framework.

A.1. On mobility simulation

To speed up computations, one city's mobility is often simulated in MATSim using a 1% population sample to test the policy cases (Axhausen et al., 2016). The practice of simulating a small proportion of the population and extrapolating the results is one of the main design principles of MATSim, and its various components are designed with this in mind. The supply simulator, based on the queue-based traffic flow model which specifically designed to balance detailed modeling with computational efficiency, is built to maintain its traffic dynamics properties when scaling the number of agents (Axhausen et al., 2016). With the scaled sample size, the simulator accurately maintains traffic dynamics by scaling both flow capacity (vehicles exiting per time unit) and storage capacity (vehicles fitting on a link) proportionally, together with teleportation function, ensuring reliable travel time calculations across different modes. This approach has been validated through numerous implementations across various cities, including Berlin Ziemke et al. (2019), Switzerland, Zurich, Munich, Brussels, and Santiago de Chile (matsim, 2014), where downscaled scenarios have been successfully calibrated. Previous studies have demonstrated that results from a well-sampled simulation model can be extrapolated to match their real-world counterparts (Llorca and Moeckel, 2019; Zhuge et al., 2019).

The remaining calibrated parameters of the MATSim Open Berlin model could be used for the Base Case simulation. For the policy cases:

- the individuals residing in the policy implementation zone and allowed outsiders are designated as the "person-internal" subpopulation and all others as the "person-external" subpopulation;
- to implement the DRZ configuration, a mode called "car-internal" that can only be used by "person-internal" is added to every car-allowed link throughout the entire network;
- in addition, the standard private car mode is removed from every link inside the DRZ, or, unlike eliminating car mode for all links, other policies could be implemented to maintain car mode on specific traversing roads within the DRZ.

Consequently, unauthorized private car owners cannot operate vehicles within the designated area, as the network links in the zone lack the standard "car" mode attribute and instead possess the "car-internal" mode. The "car-internal" mode maintains identical modeling characteristics (specifically, the same scoring parameters as default cars) in the configuration, thereby ensuring no unintended effects on the Base Case scenario. Therefore, any effects on mode choice, route choice, location choice, and departure time are solely due to changes in the utilities (e.g., lower travel time, travel costs, less penalty for activity duration obligation) of the scoring function introduced by the DRZ policies. It should be noted that the "car-internal" mode is designed exclusively for internals of the DRZ and offers sufficient flexibility to be replaced with other modes, such as bicycles or e-scooters, or to cater to different target groups in future research.

The innovation strategy configurations for trip re-planning in the simulation adhere to the calibrated parameters of the Open Berlin scenario. Two commonly used innovation strategies are included:

- the "SubtourModeChoice" strategy is used to change the mode of transportation for the trip;
- the "ReRoute" strategy offers the opportunity to replan the trip' s routes.

These two strategies allow for creating new mobility plans as candidates for plan selection. In each simulation run, 200 iterations (equivalent to 200 days) are set to observe sustained policy adoption.

A.2. On emission calculation

As the detailed distribution of engine types and corresponding (alternative) fuel consumption data for vehicles in Berlin is not currently available, which is essential for comprehensive emission modeling, traffic emissions during both warm and cold-start conditions were estimated using weighted average emission factors derived from HBEFA (Tapia-Dean and Graf, 2019). In detail, our research employs the average technique of HBEFA, which considers the traffic scenarios of different countries for the given year. The traffic scenarios incorporate the distribution of vehicle types—including Internal Combustion Engine (ICE) vehicles and Electric Vehicles (EVs)—across categories such as private cars and buses in different countries. These distributions are used to calculate weighted average emission factors for application in this research. This approach enables the model to account for variations in propulsion technologies and their associated emissions within each vehicle category.

Furthermore, it is necessary to align the road network data from OpenStreetMap with the speed limits and urban road categories, including access, local, district, trunk-city, and motorways, for feeding them to a more detailed emission model.

The analysis of traffic emissions could be performed at three different scales:

- the entire city (study area of the model),
- the zones (e.g., Traffic Analysis Zone), and
- the agent groups (for monitoring agents' behaviors in internalizing environmental costs).

The disaggregated emissions at the event level are subsequently aggregated to enable comparisons across time of day, spatial locations, and agent groups.

Appendix B. Data acquisition and mobility model validation

The mobility model we used is calibrated and validated by the MATSim development team, as documented in Ziemke et al. (2019). The calibration process involved iteratively adjusting model parameters to match observed travel behavior patterns. Key calibration parameters included:

- **Utility function parameters:** govern mode choice and activity timing decisions.
- **Activity scoring parameters:** determine the utility gained from different activity types.
- **Generalized travel cost sensitivity parameters:** control the replanning strategies (e.g., route choice, mode choice, time and location allocation).

These parameters were systematically tuned using an iterative process until the simulation outputs matched observed data across multiple dimensions. The required input data for the generation and calibration of the Berlin model includes real-world traffic data such as nation-wide census of Germany 'Zensus 2011' (Statistische Ämter des Bundes und der Lär, 2011), commuter statistics 'Pendlerstatistik 2009' (Bundesagentur für Arbeit, 2010), and local GTFS data (Verkehrsverbund Berlin-Brandenburg, 2017). Additionally, the geographical data sources used include OpenStreetMap data (OpenStreetMap, 2018), shape files describing the municipality geometries in Brandenburg, LOR (i.e., neighborhood-oriented zone system) geometries in Berlin, and CORINE land cover data (Copernicus Land Monitoring Service, 2012).

For validating various properties of travel, the Berlin SrV 2008 (Gerd-Axel Ahrens, 2009), Berlin MiD 2008 (Infas and DLR, 2010) travel surveys, and local traffic counts, BASt counts on freight traffic (Bundesanstalt für Straßenwesen (BASt), 2016) are utilized. Specifically, the model was validated against:

- **Modal split:** The simulated mode shares closely matched survey data for all transport modes (car: 29.6% vs. 30.0%, public transport: 22.4% vs. 21.0%, ride: 10.0% vs. 10.0%, bicycle: 10.6% vs. 11.0%, walking: 27.5% vs. 28.0% from MiD 2008).
- **Traffic volumes:** The model was calibrated against 8304 hourly count values from 346 count stations throughout Berlin (250 stations operated by the Berlin Traffic Management Center and 96 stations from the motorway administration), showing good correlation between simulated and observed traffic volumes.
- **Travel time and distance distributions:** Trip distances and durations showed good agreement with survey data across different modes.
- **Trip characteristics by mode:** Key metrics like average trip distance and duration were validated for each transport mode against survey data. The results showed good agreement, with differences typically within 20% for car trips (distance: 9.1 vs. 9.6 km, duration: 26.7 vs. 22.3 min) and 22% for public transport trips (distance: 9.1 vs. 11.7 km, duration: 45.1 vs. 40.2 min), while maintaining comparable accuracy for other modes of transport.
- **Departure time distributions:** The simulation captured typical daily temporal patterns, with some deviation in midday traffic volumes due to the inclusion of freight and service traffic in the simulation which were not captured in household surveys.
- **Activity patterns:** The model successfully reproduced the relative distribution of activity types (home, work, shopping, leisure, and other activities) at trip destinations. For both car and public transport trips, the shares of these simulated activities closely matched survey data, with differences typically within 5 percentage.

The validation demonstrated that the model may effectively reproduce observed travel behavior and traffic patterns in Berlin across multiple dimensions and spatial scales.

Table C.1
Emission reductions by policy area and city.

Paper	Policy	Emission reduction	
		Policy area level	City level
Policy designed for *the whole city*			
Lu et al. (2022)	*Citywide* DRP[b] for non-local vehicles and elevated expressways in Shanghai	–	57.0%–68.1% NO
Chen et al. (2023b)	*Citywide* DRP[b] in Beijing	–	52.45% CO_2, 21.98% $PM_{2.5}$
Viard and Fu (2015)	*Citywide* DRP[b] in Beijing	–	21% all air pollutants
Policy designed for *part of the city*			
Fensterer et al. (2014)	LEZ[a] in *city center* of Munich	6.8%–19.6% PM_{10}	10% PM_{10}
Yin et al. (2023)	DRP[b] in the *city center* of Paris region	85% all pollutants	4% all pollutants
Dias et al. (2016)	LEZ[a] in the *central area* of Coimbra	63% PM_{10}, 52% NO_x	−1.2% PM_{10}, −1.5% NO_x
Qin et al. (2023)	LDRP[c] in the *inner ring area* of Shanghai	−14.0% CO	Unknown
Hao et al. (2011)	DRP[b] on *limited roads* in Shanghai	8% NO_2 12% CO	Unknown
Tu et al. (2021)	DRP[b] in *densely populated city area* of Nanjing	1.6%–6.1% NO_2	Unknown
DRZ in this research	DRZ[d] on *city west* in city of Berlin	11%–47% cross all estimated air pollutants	13%–20% cross all estimated air pollutants

Note:
[a] LEZ: Low Emission Zone.
[b] DRP: driving restriction policy.
[c] LDRP: license plate driving restriction policy.
[d] DRZ: driving restriction zone policy.

Appendix C. Comparison of emission reduction effects across papers

This section compares our DRZ policies with existing emission reduction strategies implemented across various cities. Table C.1 presents a comprehensive comparison of emission reductions at both policy area and city levels, providing a comparative overview of their effectiveness.

The proposed DRZ policies demonstrate several notable achievements when compared to existing studies. First, Policy 2, while more restrictive in nature but targeting a smaller restricted area, outperforms the LEZ policy in Munich (Fensterer et al., 2014), both locally and city-wide. Second, our Policy 1 shows stronger city-level emission reductions than the Paris region study (Yin et al., 2023), when accounting for comparable emission sources (Yin et al. (2023) only includes emissions from private cars and excludes emissions from buses). While the Coimbra LEZ study (Dias et al., 2016) shows higher local reductions, our policies achieve more substantial city-wide improvements, demonstrating better overall environmental impact. These comparisons underscore the effectiveness of our targeted approach in achieving significant emission reductions while maintaining practical implementation feasibility.

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