Nationwide autonomous ridepooling in Germany: a large-scale agent-based transport simulation and external cost assessment

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Short summary

Autonomous vehicles are widely expected to generate substantial social, environmental, and economic benefits. However, these anticipated effects are still largely derived from simulations, models, and forecasts, which have so far focused predominantly on dense urban settings. This emphasis leaves an important gap, as autonomous vehicles deployed as a shared and pooled mobility service may be particularly valuable for improving accessibility and mobility in suburban and rural areas, where such benefits have rarely been assessed. Building on empirical mobile-phone origin–destination flows, this study presents the first agent-based simulation of an autonomous ridepooling system at a nationwide scale. The model represents a service operating across all of Germany, serving nearly 12 million daily rides with a fleet of 300,000 vehicles, and evaluates its implications for users, operators, and society. The results indicate a pooling rate of 77%, a mean vehicle occupancy of 1.67, and an average waiting time of 10 minutes. In addition, the system is estimated to reduce external transport costs by 3.6 billion euros annually. These findings suggest that, if effectively implemented, autonomous ridepooling could deliver substantial individual, societal, and environmental benefits not only in cities but across an entire country.

Keywords: autonomous driving; agent-based transport model; shared mobility; external costs.

1 Introduction

Shared autonomous vehicles (SAVs) are widely expected to improve affordability (Bösch et al., 2018), road safety (Di Lillo et al., 2024), efficiency (Zwick et al., 2022), and sustainability (Greenblatt & Shaheen, 2015). However, most evidence for these benefits comes from studies of dense urban areas. This urban focus leaves open a key question from a nationwide perspective on mobility access. Can these benefits be transferred to an entire country with highly heterogeneous settlement structures, demand patterns, and service conditions? Mobility provision differs fundamentally between metropolitan cores, suburban areas, small towns, and rural regions, where conventional public transport and commercial on-demand services often struggle to provide attractive and economically viable coverage. Large-scale autonomous mobility services could help address these disparities by enabling more flexible and cost-efficient operations across diverse spatial contexts. Yet no academic simulation study has comprehensively evaluated these promised benefits at a national scale while explicitly accounting for such heterogeneity.

This study addresses this gap by simulating autonomous ridepooling across Germany, covering approximately 358,000 km^2 and 11.7 million trips served by 300,000 vehicles. To enable this analysis, the MATSim framework (Multi-Agent Transport Simulation, (Horni et al., 2016)) was adapted to handle the computational demands of a nationwide scenario. The simulation allows the assessment of SAV impacts across regions with very different geographic characteristics, rather than within a single city. Based on the simulation results, the study further estimates the service quality and external cost implications. In doing so, it provides one of the first nationwide assessments of autonomous ridepooling and offers insights for policymakers, mobility providers, and operators concerned with a more equitable, efficient, and sustainable mobility system.

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2 Methodology

The input demand originates from mobile phone data provided by the data provider *Invenium Data Insights*, which contains zone-based origin-destination flows in 60-minute bins in Germany for two weeks, one in September 2023 and one in November 2023. The zones vary in size depending on the number of mobile activities within them, ranging from 250 m × 250 m to 1 km × 1 km. Figure 1 shows how the different zone sizes are spatially distributed. We extract an average day of the two weeks, covering 276 million movements in all of Germany, for further work. Only trips of lengths between 1.5 km and 50 km are considered, as the service is not designed for long-distance trips. In total, 157 million movements are considered.

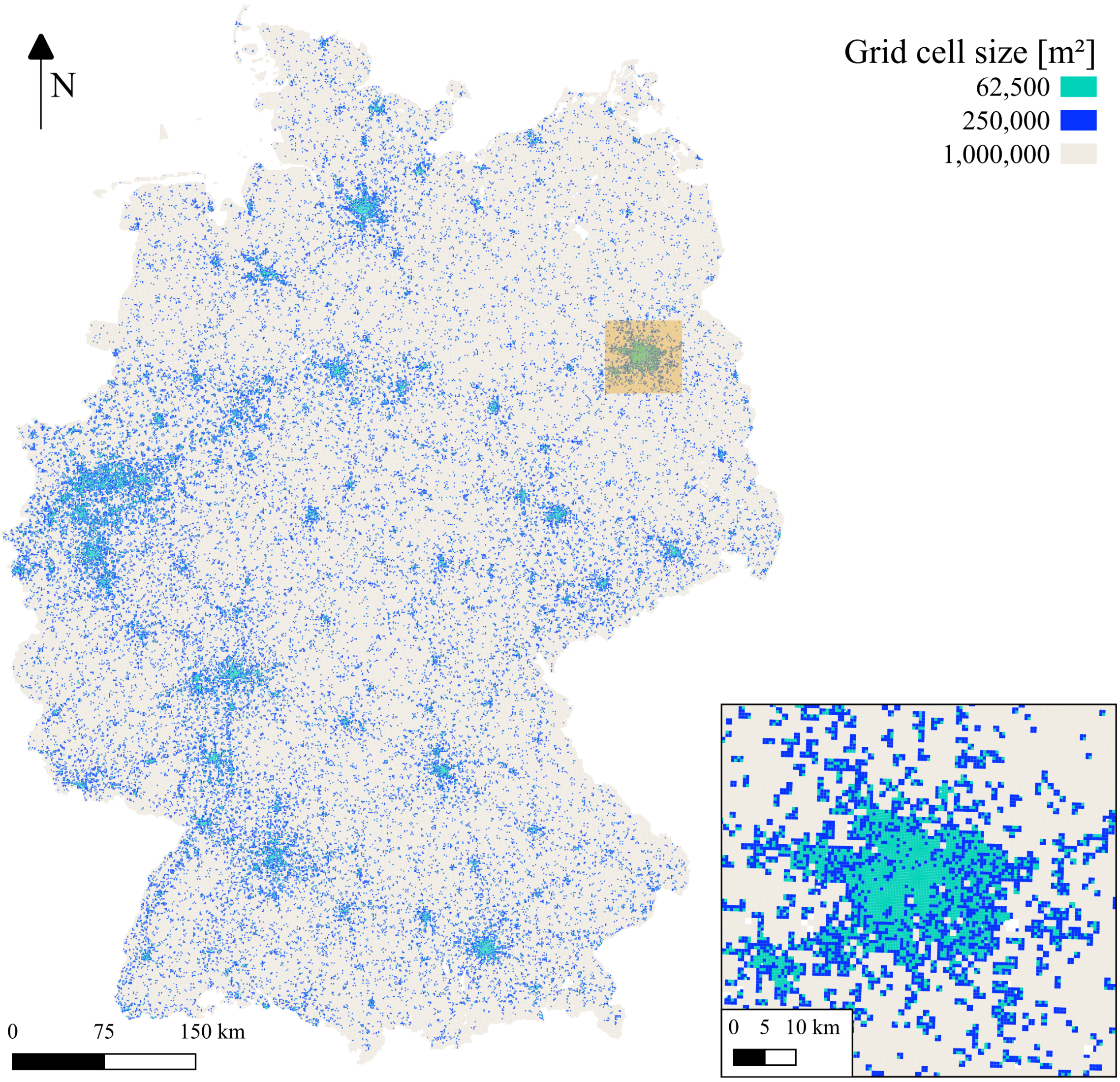

Figure 1: Raster cells of geo-coded mobile phone data for Germany and Berlin.

To assign specific trips to the new autonomous service, movements are assigned to one of the conventional modes: *car*, *car passenger*, *bike*, or *public transportation (i.e., bus or rail)*. For the mode assignment, Germany's largest mobility survey, MiD (Mobilität in Deutschland, Nobis & Kuhnimhof (2018)), is used to categorize modal splits by distance and travel time, as well as by structural and socio-demographic attributes. For each combination of distance and travel time, the MiD data provides a modal split used for assignment in the trip data. In addition, the settlement structure in which the trip starts is taken into account to reflect a shift in the modal split in urban areas with high PT volumes. Settlement structure is taken from the Regional statistical spatial typology (RegioStaR) of the German Federal Ministry for Digital and Transport (BMDV, 2025).

Figure 2 illustrates the further process of demand generation for the new autonomous ridepooling service. The 157 million daily movements with the assumed modal split are assigned to the new autonomous mode by randomly allocating 10 % of all car trips, 20 % of all car passenger trips, and 5 % of all bus and rail trips, resulting in 11.9 million requests. The requests' origins and destinations are randomly assigned to a location within the respective zones, and their departure times are randomly assigned to a 60-minute time bin. The demand applies to group bookings with a maximum group size of 4 people.

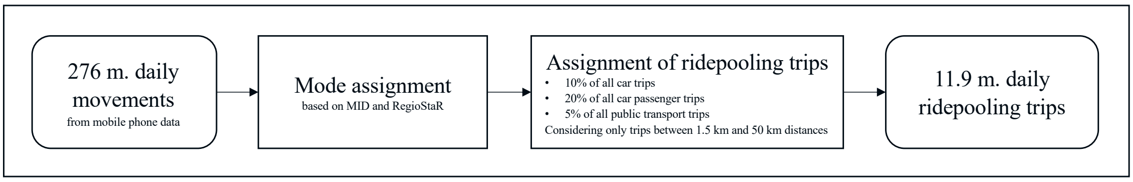

Figure 2: Visualization of demand generation based on mobile phone data and mode shares.

300,000 vehicles are deployed in the MATSim simulation and routed on the German main road network. The vehicles have four seats. Given the large number of vehicles and thus the resulting simulation times, no operational constraints, such as charging, hub returns, maintenance, or similar, are considered. Previous simulations showed that charging limitations result in a 2 % to 7 % drop in efficiency, depending on the density of charging facilities (Zwick et al., 2022). The vehicles are distributed in hubs with a given capacity of 20 vehicles per hub. The hub locations are distributed randomly across the network, weighted by demand density. As such, the supply mirrors the demand distribution.

To evaluate the environmental impact of the service, we assessed the anticipated external costs of its implementation relative to the external costs saved. The analysis focuses specifically on the effects of mode shifts from private cars to SAVs and from PT to SAVs. This study applies the findings of Allekotte et al. (2020) and Van Essen et al. (2020) to represent private internal combustion engine vehicles (ICEV) with an average external cost of 0.15 € per person-kilometer (pkm) and PT with an average external cost of 0.05 €/pkm. As there exists no aggregate estimate of each external cost category for SAVs, the methodology scales the external costs associated with ICEV in Table 1. The scaling is subject to research that analyzes and quantifies the impact of an electric autonomous ridepooling service on each external cost category compared to the private car.

Table 1: SAV environmental external costs on kilometer basis

	Car		**SAV**		
Externality	€/pkm	Source	Change	Source	€/pkm
Accident	0.051	Allekotte et al. (2020)	88 % reduction	Di Lillo et al. (2024)	0.006
Noise	0.015*	Allekotte et al. (2020)	13 % reduction	Zwick et al. (2021)	0.013*
Congestion	0.044	Van Essen et al. (2020)	no difference	Narayan et al. (2022)	0.044
Infrastructure	0.002	Allekotte et al. (2020)	no difference	Low et al. (2022)	0.002
Vehicle	0.012	Allekotte et al. (2020)	11 % increase	Kemp et al. (2020)	0.014
Operation (TTW)	0.032	Allekotte et al. (2020)	full reduction	Cai et al. (2022)	0
Energy (WTT)	0.006	Allekotte et al. (2020)	80 % reduction	FIS (2023b)	0.001
Land-use	0.004	Allekotte et al. (2020)	no difference	Narayan et al. (2022)	0.004

*Noise is based on vehicle kilometers traveled

3 Results

The agent-based simulation reveals detailed insights into the operation of the large-scale ridepooling service with 300,000 SAVs. From a user perspective, the service is quite attractive, with a mean waiting time of 10:26 minutes and a mean detour of 17.5 %. At the same time, the high demand leads to a rather efficient service, with a mean occupancy of 1.67 and an empty-kilometer share of 20 %. Whereas the mean occupancy can be elevated in systems with high detours, the fleet efficiency η provides a less biased measure of efficiency. The definition of η is taken from Liebchen et al. (2020) and is defined as the ratio of the passenger kilometers booked, d_{pkb}, i.e., the direct distance without detours, to the vehicle kilometers traveled, d_{vkm}:

$$\eta = \frac{d_{\text{pkb}}}{d_{\text{vkm}}} \quad . \tag{1}$$

In our simulation, η is 1.43 and can be compared to the average occupancy of private cars in Germany (*excluding* parking search). With a share of 77 %, more than three-quarters of all rides are pooled. Figure 3 shows the occupancy of the vehicles over the course of a day. The states 0 to 4 indicates how many customers each vehicle is carrying.

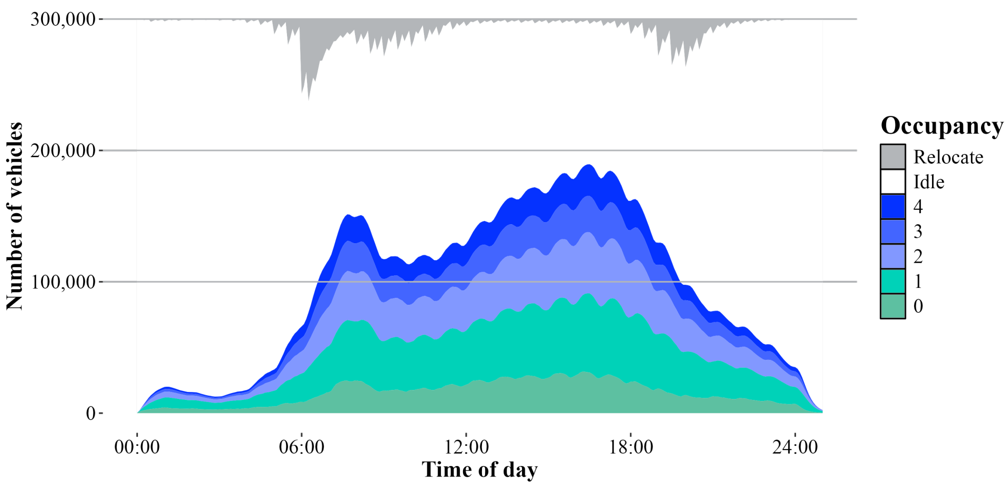

Figure 3: Vehicle occupancy during the simulated day.

Figure 4 shows the spatially distributed average wait time in Germany. It can be observed that in most areas a maximum average wait time of 10 to 20 minutes is reached. Some areas indicate lower service quality, likely due to a selective vehicle shortage. A deeper look at the data revealed that natural barriers, such as rivers, can cause vehicle misplacement: the relocation algorithm places vehicles on one side of a river and assumes good vehicle coverage of a zone, even when the travel time to a pick-up is high. This example reinforces the need for detailed service planning.

The shifts in pkm and vkm traveled from cars, buses, and trains to SAVs drive changes in the external cost assessment. The introduction of SAVs cannibalizes 10 % of all car trips with a distance of 50 km or less. The total vkm in Germany in 2019 was 628,000 million km (Kraftfahrt-Bundesamt (KBA), 2023). Given an average private vehicle occupancy of 1.5 (FIS, 2023a), total pkm amounted to 942,000 million km. According to Nobis & Kuhnimhof (2018), 60 % of all vkm occur within a travel distance of up to 50 km. Consequently, 37,680 million vkm and 56,520 million pkm are being replaced by SAVs. This saves 8,528 million € in external costs from car travel. A separate analysis for car passengers is not required, as they are inherently accounted for through the average vehicle occupancy. Furthermore, 5 % of PT trips are now served by SAVs. The total pkm for local PT amounts to 111,000 million km, of which 38,000 million km are completed by bus and 73,000 million km by rail-based transport (Verband Deutscher Verkehrsunternehmen, 2021). By definition, local PT trips are limited to a maximum distance of 50 km. A 5 % modal shift results in a reduction of 5,550 million pkm and saves 0.3 million €. The autonomous ridepooling service itself generates 5,212 million € in externalities from its 39,785 million vkm and 66,795 million pkm. The estimated social benefit of a Germany-wide autonomous ridepooling service is then 3,601 million € per year.

A univariate sensitivity analysis is performed on each of the SAV change factors applied to the different externalities to determine their impact on social benefit (figure 5). The SAV change factor applied in Table (1) indicates how much better or worse the autonomous ridepooling vehicle is expected to be than a private car. Therefore, we only analyze the externalities in which a difference

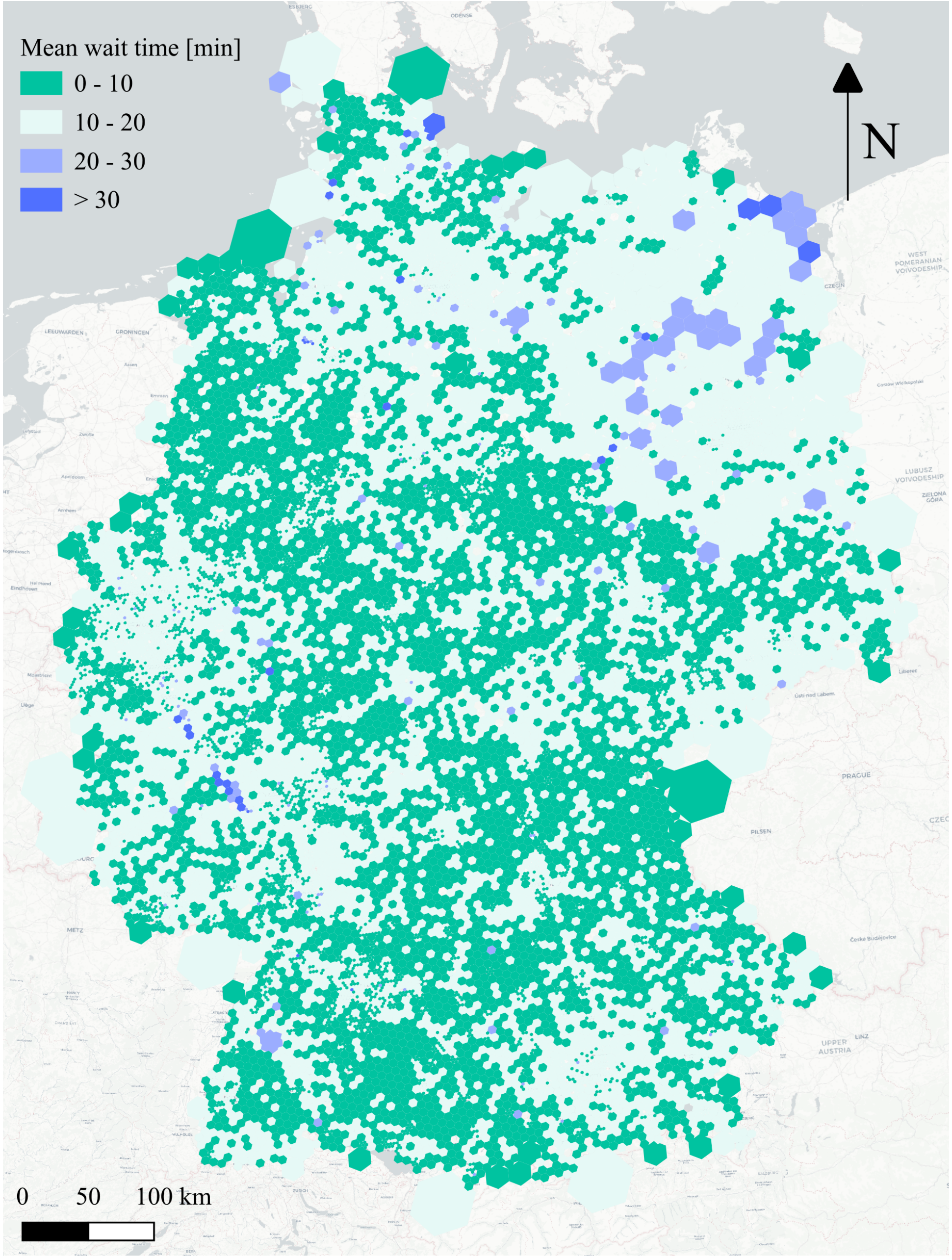

Figure 4: Spatially distributed mean wait time.

between the modes is assumed. If the SAV change factor is 1, the SAV has the same impact on the environment and society as the car. The most significant contributors to social benefit are reductions in accidents and operational efficiencies. Energy consumption, noise reduction, and external costs of vehicle production have a relatively minor impact on overall societal benefits. The social benefit remains positive under the given assumptions and across most analyzed scenarios. The only scenario where social benefit might become negative is when SAVs significantly increase accident rates. This scenario, however, is very unlikely, given the analysis of current autonomous driving data (Di Lillo et al., 2024).

4 Conclusions

This study presents a large-scale simulation of a nationwide autonomous ridepooling system in Germany, covering 11.7 million trips served by 300,000 vehicles across 358,000 km². The research evaluates both the operational dimensions and external cost implications of deploying shared autonomous vehicles on a national scale.

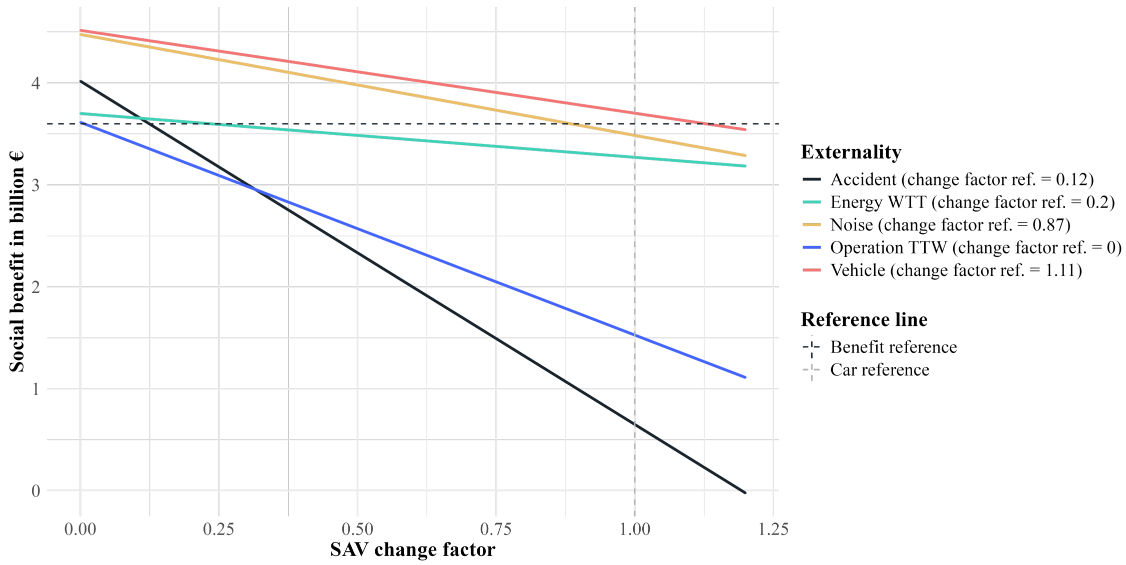

Figure 5: Univariate sensitivity analysis of social benefit on SAV change factor.

There exist several limitations. Demand and mode-shift assumptions are highly uncertain, transfer rates are simplified, and intermodal, induced, and purpose-specific demand effects are omitted. The simulation includes only main roads, likely overstating service KPIs because substantial access walking is excluded from reported waiting times. Operational processes such as charging and cleaning are ignored. A single national dispatcher and unchanged public transport supply simplify real-world governance and integration. External cost parameters and non-simulated mode effects rely on external studies and assumptions, and the aggregate analysis cannot capture regional, temporal, or social differences in impacts.

However, the results underscore the potential of an autonomous ridepooling system to provide efficient and accessible mobility for all. The simulated SAV service achieves superior passenger occupancy compared to the private car and high fleet efficiency with 77 % of its trips pooled. The average time it takes to get a ride is less than 11 minutes. This demonstrates that autonomous ridepooling can effectively address mobility demand across diverse geographic regions and significantly boost accessibility in rural areas.

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