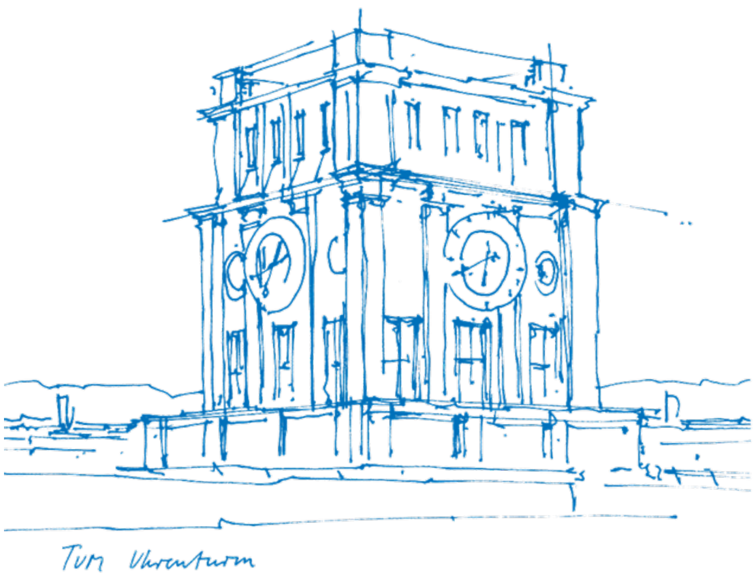
Professorship of Mobility Policy
TUM School of Social Sciences and Technology
Technical University of Munich

Public Transport through Time and Space: Novel Indicators for Fare Policy Assessment

Martin Schlett

Allister Loder

Arbeitsbericht Mobility Policy 4 **December 2024**



Public Transport through Time and Space: Novel Indicators for Fare Policy Assessment

Martin Schlett
Professorship of Mobility Policy
Technical University of Munich
DE-80333 Munich
martin.schlett@tum.de

Allister Loder
Professorship of Mobility Policy
Technical University of Munich
DE-80333 Munich
allister.loder@tum.de

December 2024

Abstract

In times of severe budget constraints, businesses and governments across the globe assess the impact of public transport fare innovations such as the Deutschlandticket or fare-free public transport. Studies analyzing the impact of fare innovations on individual travel behavior have not yet exploited the spatial and temporal insights provided by novel smartphone-based tracking data. Our paper addresses this gap, introducing four novel indicators that are simple yet insightful: (a) the generalized cost of travel in fare associations based on GPS trajectories, (b) the travel distance per weekday and fare zone, (c) the activity time per fare zone, and (d) the travel direction per mode and zone of residence. The methodological relevance of these indicators for public transport fare innovation assessment is discussed by applying the indicators to the case of the Deutschlandticket. We use multi-month semi-passive smartphone-based tracking data to assess the impact of the Deutschlandticket. The results show that the effects of the Deutschlandticket exceed purely monetary benefits and vary across fare zones, weekdays, and times of year. The paper contributes to the assessment of the Deutschlandticket and expands scientific methods for assessing public transport fare policy innovations. The generalized cost of travel is calculated based on GPS trajectories. Spatial and temporal dimensions of activity time, trip distance, and trip direction are integrated into one assessment, creating new insights for urban planning and equity analysis. Public transport operators can use the indicators to optimize revenue distributions and adapt fare structures.

Keywords

Deutschlandticket, smartphone-based GPS tracking, generalized cost of travel, spatial equity, time geography

Suggested Citation

Schlett, M. and A. Loder (2024) Public Transport through Time and Space: Novel Indicators for Fare Policy Assessment. *Arbeitsberichte Mobility Policy*, **4**, Technische Universität München.

1 Introduction

Worldwide, transit organizations, cities, and countries are innovating their fare policies: Luxembourg (Bigi *et al.*, 2023; Gillard *et al.*, 2024) and Tallinn (Cats *et al.*, 2017; Kebłowski *et al.*, 2019) introduced Fare-Free Public Transport (FFPT), Austria (Follmer and Treutlein, 2023; Wallimann, 12.01.2024) introduced the Klimaticket, and digital or smartphone-based ticketing has become dominant (Aguiléra and Boutueil, 2019). Among those innovations, the Deutschlandticket (D-Ticket), a low-cost fixed-rate travel pass for PT in Germany as described below, is Germany's most prominent and radical fare innovation in recent decades. Considering the high costs of 3 billion annually in public subsidies (Die Bundesregierung, 2023), its assessment has become crucial and a dominant subject of public debate. However, many traditional assessment approaches fail to capture critical dimensions of the D-Ticket, which is supposed to simultaneously accomplish financial relief, climate mitigation, and increased attractiveness of Public Transport (PT) (Die Bundesregierung, 2024b). This study introduces four novel indicators that exploit innovative data to address previously neglected dimensions of fare innovation assessment, specifically how their impacts vary across space and time.

Today, mobility policy goals increasingly focus on sustainability, accessibility, and mobility justice. Cost efficiency and political feasibility remain essential. Societies across the globe try to achieve the United Nations Sustainable Development Goals (UN SDGs) (United Nations Department of Economic and Social Affairs, 2024). Assessing sustainability, equity, and resilient mobility infrastructure systems becomes essential for assessing mobility policy. Many cities and countries strive to reduce emissions and inequalities in mobility by reducing car traffic and shifting demand towards public transport (PT) with PT fare innovations (Gallo and Marinelli, 2020). Pricing and regulation are no novel measures but are increasingly tailored towards PT and active mobility instead of cars, including the redistribution of urban space for increased accessibility and equity (Oviedo *et al.*, 2022; Hackl, 2018; Bertolini, 2020). Introducing FFPT or low-cost fixed-rate travel passes has been an especially prominent approach in Europe over the past few years (Cats *et al.*, 2017; Follmer and Treutlein, 2023; Dutra, 2019; Verband Deutscher Verkehrsunternehmen e. V. *et al.*, 16.12.2022). In times of severe budget constraints on businesses and governments, assessing the impact of fare policy decisions is crucial, especially for costly PT fare innovations.

Literature on the impact assessment of PT fare innovations reaches back decades, primarily using established indicators like trip numbers, distances, and travel durations based on travel diaries, even though the data collection methods have changed. Meanwhile, smartphones have become a dominant factor in human life and mobility, changing how people navigate and buy tickets (Khan *et al.*, 2020; Arslan *et al.*, 2016). Regarding Mobility-as-a-Service

(MaaS), the smartphone is used for information, pricing, and data collection (Hörcher and Graham, 2021; Kamargianni *et al.*, 2016). The potential to use smartphone-based travel data for mobility assessment has long been recognized (Schelewsky *et al.*, 2014). Smartphone-based tracking data provide a valuable alternative to transport operators dismantling physical ticketing infrastructure due to digital solutions or FFPT. In both cases, traditional fare card data will no longer be available (Lu *et al.*, 2024). Tracking data covering a period before and after the introduction of the D-Ticket (Loder *et al.*, 2023) bears potential for further analysis of combined temporal and spatial dimensions. This potential encompasses activity time at different locations, which is the primary motivation for mobility (Mokhtarian and Salomon, 2001). This paper contributes to the debate on the benefits of the D-Ticket and advances the methodology of public transport fare innovation assessment. This paper provides the first results on the spatial distribution of generalized cost of travel (GCT) and activity time changes due to the D-Ticket. To the best of our knowledge, this study is the first to calculate GCT based on GPS trajectories for a multi-month panel and the first to integrate multi-month activity time measures in fare innovation assessment. Moreover, we introduce travel direction as a new level of analysis, which is especially relevant for fare associations. These indicators offer novel insights into individual travel after introducing the D-Ticket. The analysis is based on the smartphone-based tracking panel *Mobilität.Leben* (Loder *et al.*, 2023) and sharpens previous assessments of the D-Ticket.

The following sections provide an overview of established and innovative data and indicators used to assess European fare policy interventions. The change in cost-benefit ratio from previous fare regimes to the D-Ticket is so immense that this study addresses the D-Ticket in the context of FFPT. The following section describes the data and methodology, introducing the novel indicators for mobility policy assessment. The results of these novel indicators are presented for the case of the Deutschlandticket, and their relevance is discussed at the end of the paper.

2 Common indicators for fare policy assessment

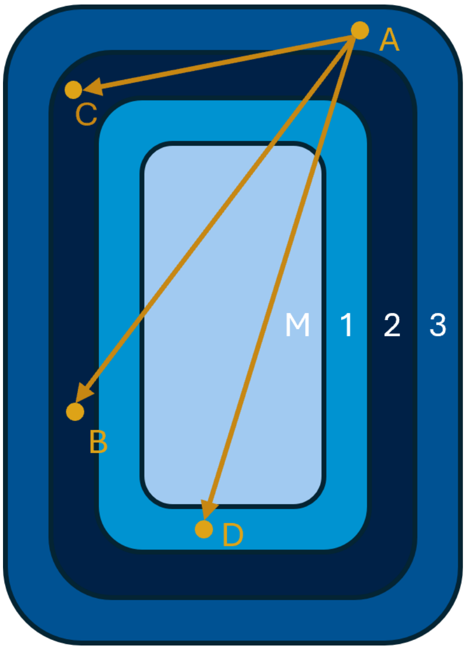
2.1 Background: Travel pass fare policy in the DACH-Region

PT fare structures in Germany, Austria, and Switzerland (DACH-Region) are determined by so-called fare associations (Tarifverbünde) and fare zones (Tarifzonen). In these fare associations, travelers can use all transport modes with one ticket. The price is based on geographically traversed fare zones. Although a municipally owned transport company often provides urban transport in large cities, numerous transport providers of various sizes in any region offer one or multiple modes of PT. To simplify ticket purchases and distribute revenue fairly among companies, transport providers in and around Hamburg established the first fare association, the Hamburger Verkehrs Verbund (hvv), in 1965. The fully integrated regional and urban PT soon became standard within the DACH region (Buehler *et al.*, 2019). In recent years, innovative concepts for MaaS and more individual pricing, such as the homezone, have been developed (Weigele *et al.*, 2021). In this concept, the price is determined by the modes, area, and time interval that the traveler can freely choose and thereby define an individual zone of everyday mobility around their home.

The Münchener Verkehrs- und Tarifverbund (MVV) provides bus, tram, regional trains, suburban trains, and underground services to 2.9 million in 176 municipalities in one integrated fare structure (Münchener Verkehrs- und Tarifverbund, 2021a). Until 2023, the area was divided into seven fare zones: a central zone *M* and decreasingly central zones 1 through 6. Travelers are priced based on which and how many fare zones they cross on their trip; the correct price can be determined from a price list as simplified in Figure 1. This structure is exemplary for many other fare associations across the DACH-Region which improve the service quality for users and exploit synergies among transport providers. They use unified tickets and coordinate lines and stations to make transit easier and more efficient for travelers (Pucher and Kurth, 1995). The regional integration of prices, schedules, and services contributed to a higher PT demand in international comparison (Buehler and Pucher, 2012). While travelers only need one ticket while traveling within the area of each association, a new ticket is required for every additional association the traveler enters. Multiple tariff zones may exist within each transport association, and travelers must determine the cost based on the area, distance, and time of each trip (Pucher and Kurth, 1995).

The MVV offers travel passes for a specific period, e.g., day, week, month. They are valid for a particular part or the entire area of the MVV and cost up 227.50€ per month (Münchener

Figure 1: Ticket Prices Depend on the Fare Zones Passed. Own Figure based on (Münchener Verkehrs- und Tarifverbund, 2021b).



Trip	Zones	Category	Price
A to B	M, 1, 2, 3	M - 3	9.70€
A to C	2, 3	2 - 3	3,90€
A to D	M, 1, 2, 3	M - 3	9,70€

	M 1 - 2 2 - 3	M-1 1 - 3	M - 3
Single Trip	3.90€	5.80€	9.70€
Day pass	9.20€	10.50€	12.70€

Verkehrs- und Tarifverbund, 2021b). Before the D-Ticket, they were the cheapest option for regular travelers. After purchasing the travel pass up-front, each trip with PT is conducted at zero marginal monetary cost (Larsen and Rekdal, 2010).

2.2 Recent PT fare innovations in Germany

Like its predecessor, the 9-Euro-ticket (Die Bundesregierung, 2024a), the D-Ticket combines two innovations: the abolishment of fare zones and a radical price reduction. A monthly ticket for the MVV would have cost 227.50€ (Münchener Verkehrs- und Tarifverbund, 2021b) per month, whereas the D-Ticket provides public local and regional transport throughout Germany for 49€ per month. The official government objectives for this intervention were financial relief and a shift towards more sustainable transport (Die Bundesregierung, 2024b). Several studies analyzed the D-Ticket (Loder *et al.*, 2023; Verband Deutscher Verkehrsunternehmen e. V. *et al.*, 16.12.2022; O2 Telefónica, 2023; Loder *et al.*, 2024; Krämer and Korbutt, 2022; Rozynek *et al.*, 2023; Suckow *et al.*, 2023). They drew on different data sources from online and phone surveys (Krämer and Korbutt, 2022; Suckow *et al.*, 2023), representative online interview panels (Verband Deutscher Verkehrsunternehmen e. V. *et al.*, 16.12.2022) and tweets (Suckow *et al.*, 2023), to tracking panels based on phone registration data (O2 Telefónica, 2023) or smartphone-based GPS tracking (Loder *et al.*, 2024; Gaus *et al.*, 2023). The 9-Euro-ticket has been studied regarding equity based on the number of trips and the share of mobility costs of household income (Rozynek *et al.*, 2023), but also from a company perspective (Krämer and Korbutt, 2022) analyzing ticket ownership per user groups, number of trips, modal shift from car to PT, and subjective preferences to (not) purchase the D-Ticket. A large study based on phone data (O2 Telefónica, 2023) focuses on the number of trips per mode and weekday. A comprehensive study from 2022 (Verband Deutscher Verkehrsunternehmen e. V. *et al.*, 16.12.2022) discusses attitudes, satisfaction, number and distance of trips per mode, and degree of urbanization. Moreover, the impact of 9-Euro- and D-Ticket on travel behavior was analyzed regarding average daily travel distance, change in modal share, and GCT (Loder, 2024). Overall, the studies find an increased number of trips and travel distance, decreased travel costs for owners of the D-Ticket, and a shift from car to PT.

2.3 Fare Policy Assessment

Low-cost fixed-rate seasonal tickets and FFPT are two pivotal examples of pricing policies. They have been introduced on different levels and with varying objectives for decades (Stadtverwaltung Templin, 2019; Cats *et al.*, 2017; Busch-Geertsema *et al.*, 2021; Bull *et al.*, 2021; Dutra, 2019). Today, the distinction between free PT and FFPT (Cats *et al.*, 2017) highlights that FFPT is not generally "free" because of non-monetary and external costs (Schröder *et al.*, 2023). The decision-making process behind the FFPT introduction in Luxembourg (Gillard *et al.*, 2024) and Tallinn (Kebłowski *et al.*, 2019) have been addressed qualitatively. Quantitative methods offer a macro-perspective on the change in travel behavior; one of the first studies to perform such a data-driven on the impact of FFPT (Baum, 1973) estimated demand response to free PT using out-of-pocket cost, access cost, access time, cars per capita in the zone of residence, and median household income in the zone of residence. Over the past three decades, technology to collect, process, and analyze data has improved. This paper distinguishes between established indicators summarised in Table 1 and innovative indicators summarised in Table 2. Among the innovative indicators, the most recent approaches rely on GPS tracking panels used to analyze transport as early as 1996 (Wagner, 15.09.1997). However, only with the smartphone, widespread availability of mobile internet connection, and automated trip and mode detection software did the method reach its current potential (Schelewsky *et al.*, 2014). Passive tracking methods are still prone to errors; tracks may be incomplete, and trips or modes may be wrongly classified (Schelewsky *et al.*, 2014). One of the first studies to assess fare policies based on GPS-tracking via a smartphone app is conducted on the effects of the Klimaticket in Austria (Follmer and Treutlein, 2023), creating valuable insights into the purchase and use of the ticket.

The Mobilität.Leben study (Loder *et al.*, 2023) is a further tracking panel based on semi-active travel diaries focusing on one metropolitan region over 19 months.

2.4 Established indicators

Switzerland introduced the Generalabonnement (GA) many years ago, motivating several studies that assess its impact. One of the earliest studies on the GA (Simma and Axhausen, 2001) is based on ownership (car or GA), number of trips, and distance traveled per mode. The person kilometers and mode share are essential indicators in other studies targeting Covid-19 response (Molloy *et al.*, 2021a) or externalities (Molloy, 2021) based on the passive GPS travel diaries in the MOBIS study (Molloy *et al.*, 2022), or revenue based on simulation (Weibel *et al.*, 2024). After Tallinn introduced FFPT in 2013 (Cats *et al.*, 2017), one study analyzed the modal split based on the number of trips, as well as the travel distance per mode, accessibility in terms of days without travel and employment opportunities, and equity, distinguishing between multiple societal groups (Cats *et al.*, 2017). A trial experiment was conducted in Santiago de Chile (Bull *et al.*, 2021), offering free PT ridership to a sample group of citizens and collecting active travel diaries. These travel diaries were then used to derive mode share, number of multi-modal trips, time allocation to work, travel, and leisure, as well as the time of day for each trip in the context of peak and off-peak travel (Bull *et al.*, 2021). Germany introduced the 9-Euro-Ticket in 2022 and its successor, the D-Ticket, in 2023. Already before, specific cities or regions had introduced FFPT. The most prominent case is Templin, where PT was fare-free from 1997 through 2003. Since 2003, the city has operated a heavily subsidized urban transport (Stadtverwaltung Templin, 2019). A study from 2003 (Storchmann, 2003) looked at ridership numbers, modal split based on trip numbers, and externalities such as emissions, fatalities, and casualties. The introduction of FFPT for state employees in the German state of Hesse (Busch-Geertsema *et al.*, 2021) was analyzed regarding the effects on the regularity of mode usage and attitudes based on commute distance and subjectively perceived accessibility. Data stemmed from two quantitative online surveys from 2015 and 2019. More recently, the 9-Euro-Ticket and D-Ticket caused many scientific studies on its various effects. Based on traditional survey data, another study (Andor *et al.*, 2023) focused on user satisfaction, average trip savings, and emission reductions before performing a cost-benefit analysis on the 9-Euro-Ticket intervention as a measure to reduce negative climate impact (Andor *et al.*, 2023). The identified established fare policy impact assessment indicators are summarised in Table 1. None of these indicators offers a high resolution of individual locations in time and space. Moreover, data sources that rely on active answers by the respondents are prone to errors as mistakes and manipulations by respondents can never be fully avoided (Mouter *et al.*, 2021).

Table 1: Overview of established indicators for PT fare policy assessment.

Case	Study	Indicator	Data
Switzerland, Generalabonnement	Simma and Axhausen (2001)	– Car & GA ownership – Trips – Distance – Person kilometers – Mode share	Passive GPS travel diaries
Switzerland, Generalabonnement	Molloy (2021); Molloy *et al.* (2022)	– Covid-19 response: distance per mode – Externalities	Simulation data
Estonia, FFPT (Tallinn)	Cats *et al.* (2017)	– Modal split – Travel distance – Accessibility – Equity (income, employment, age, gender)	Ticket sales data
Chile, FFPT trial (Santiago de Chile)	Bull *et al.* (2021)	– Mode share – Multi-modal trips – Time allocation – Peak/off-peak travel	Active travel diaries
Germany, FFPT (Templin)	Storchmann (2003)	– Ridership – Modal split – Externalities (emissions, fatalities, casualties)	Ridership data
Germany, 9-Euro-Ticket	Andor *et al.* (2023)	– User satisfaction – Trip savings – Emission reductions – Cost-Benefit Analysis	Active surveys
Germany, FFPT for State Employees (Hesse)	Busch-Geertsema *et al.* (2021)	– Regularity of mode usage – Commute distance – Perceived accessibility	Online surveys

2.5 Innovative indicators

Several studies applied established indicators to novel data sources, others used novel indicators or methods based on established data sources as summarised in Table 2. An example of the latter is given by the analysis of FFPT's impact on Luxembourg (Bigi *et al.*, 2023) which introduced FFPT in 2020 (Dutra, 2019). Based on a survey with 33.000 respondents from 2017, a MATsim model was calibrated, and an analysis of the estimated impact of FFPT on car usage among different user groups was performed (Bigi *et al.*, 2023). They used established indicators like transport mode, travel time, travel distance, origin, and destination for each trip and aggregated the total travel distance and duration per person. However, estimating these from a synthetic population simulation rather than stated or revealed choice data is a new approach. Another example of established indicators applied to novel data is given in the Klimaticketreport (Follmer and Treutlein, 2023) based on semi-passive travel diaries. Austria introduced the Klimaticket in October 2021. Owners of such a Klimaticket can use public local, regional, and long-distance transport throughout the country. The Klimaticketreport 2022 (Follmer and Treutlein, 2023) focused on analyzing customer groups, repurchase rates, how many rail kilometers each owner travels on average per year, and how high the estimated emission reductions attributed to the Klimaticket are. The emission reductions are estimated based on statements by active survey respondents about the alternative for specific trips.

Similar approaches can be found in the context of assessments of the D-Ticket and its predecessor, the 9-Euro-ticket. Based on a passive tracking panel, one study used travel distance per mode and number of trips per mode as leading indicators (Gaus *et al.*, 2023). They further considered trip purposes and purchasing numbers. The study finds that overall travel increased with most new trips bound to PT, but modal change, especially from cars, was only a marginal factor. Another study uses Google Popular Time (GPT) to assess the impact of the 9-Euro-ticket on crowding in PT stations (Lu *et al.*, 2024). It is one of few studies that have analyzed the effects of PT fare innovations on a micro-level using phone-based data. The largest representative study on the 9-Euro-ticket (Verband Deutscher Verkehrsunternehmen e. V. *et al.*, 16.12.2022) is based on 80,000 online interviews before, after, and during the validity period of the 9-Euro-ticket. The study analyzed various indicators, most importantly, the number of trips, trip distance, mode choice, trip alternatives, trip purpose, regional dimension of the trip, and socioeconomic data, including the location of residence and its degree of urbanization. The regional dimensions are particularly innovative in fare policy assessment. They found an increase in the overall number of trips and average trip distance as well as a modal shift from car and active mobility to PT in the validity period. Owners of the 9-Euro-ticket conducted more trips outside their fare association than those without the 9-Euro-ticket, and the quantity of travel and 9-Euro-ticket usage decreased with a decreasing degree of urbanization. Overall, the diversity of studies, data sources, and results led to, at times, contradicting and hasty interpretations (Krämer, 2024).

Beyond the policy interventions discussed so far, other studies focused on additional aspects that have not been addressed in the context of FFPT or low-cost fixed-rate travel passes. One such aspect is the equity of accessibility between different locations (Tiznado-Aitken *et al.*, 2021; Zhao and Zhang, 2019), without temporal differentiation. Multiple scholars analyzed the monetary travel cost in different pricing regimes to research the impact of different fare structures on accessibility and equity (Tiznado-Aitken *et al.*, 2021; Zhao and Zhang, 2019; Rubensson *et al.*, 2020; Silver *et al.*, 2023). Another study integrated data on individual travel, tracked via a smartphone app, with survey data on energy, residential choice, social networks, and important life events (Calastri *et al.*, 2020). The study enables research on the cross-cutting effects of multiple phenomena usually addressed in solitary. An overview of GPS tracking methods and their application before 2016, dating back to 1997, can be found in (Schönau, 2016). More recently, GPS tracks were used to study the external travel costs (Molloy *et al.*, 2021b). Overall, smartphones have become a powerful tool for transport researchers (Schelewsky *et al.*, 2014). Beyond fare policy, scholars in the field of time geography started to address dynamic accessibility (Ryan *et al.*, 2023), the accessibility of locations or people in dependence on both time and space. However, such studies mostly rely on active travel surveys (Kwan, 1998; Neutens *et al.*, 2012; Ryan *et al.*, 2023) or simulations (Fajardo-Magraner *et al.*, 2023) and could benefit from modern tracking data and innovative indicators. In summary, scientific assessment of fare policy innovations often uses traditional data with low resolution or without combined temporal and spatial information, or it does not exploit the potential of novel GPS tracking panels in this regard.

Table 2: Overview of innovative indicators for PT fare policy assessment.

Case	Study	Indicator	Data
Luxembourg, FFPT	Bigi *et al.* (2023)	– Standard descriptive indicators – MATsim model	Large active survey (33,000 respondents)
Austria, Klimaticket	Follmer and Treutlein (2023)	– Customer demographics – Repeat purchases – Rail kilometers – Estimated emission reductions	Semi-passive travel diaries, active surveys
Germany, D-Ticket	Gaus *et al.* (2023)	– Travel distance per mode – Number of trips per mode – Trip purposes – Purchasing numbers	Passive tracking panel
Germany, 9-Euro-Ticket	Lu *et al.* (2024)	– Crowding in PT stations	Crowdsensing data (Google Popular Times)
Germany, 9-Euro-Ticket	Verband Deutscher Verkehrsunternehmen e. V. *et al.* (16.12.2022)	– Number of trips – Trip distance – Mode choice – Trip alternatives – Trip purpose – Regional dimension – Socioeconomic data	80,000 online interviews
Germany, 9-Euro-Ticket	Krämer (2024)	– Overall travel volume – Modal shift – Travel outside fare associations – Urbanization effect	Mixed data sources

3 Method and Data for Novel Indicators

The novel indicators are developed based on the identified research gaps and available information in the Mobilität.Leben data (Loder *et al.*, 2023). GPS tracking panel data (Loder *et al.*, 2023; Molloy *et al.*, 2021b; Follmer and Treutlein, 2023) represent a novel quality and detail of information on individual travel behavior. The Mobilität.Leben study (Loder *et al.*, 2023) collected semi-active GPS-based travel diaries using a custom-made smartphone app. The app tracked every trip, including departure and arrival times, speed, and exact route. The app further assigned a transport mode and purpose to each trip which the user could validate or correct. This combination of automated tracking and classification of trips with active validation by users is called semi-passive travel diary (Victoria Dahmen *et al.*, 2023). were collected from June 2022 through December 2023, covering the end of COVID restrictions, the 9-Euro-ticket, and the introduction of the D-Ticket in May 2023. The details on study design and data processing performed before this study are outlined in (Loder *et al.*, 2023) and (Victoria Dahmen *et al.*, 2023). For each trip, the data provides location, start and end time, trajectory, distance, duration, main mode, as well as purpose and duration of the next and previous stay. Additional variables were introduced during data processing to indicate whether a trip is in Germany and within the MVV (Victoria Dahmen *et al.*, 2023). The tracking data is enriched with sociodemographic data collected in multiple online surveys (Loder *et al.*, 2023). For this study, additional filtering is performed. Trips that fulfill one or more of the following criteria are excluded:

1. Duration longer than 24 hours.
2. Trip entirely outside of Germany.
3. Trips with main mode airplane or (long-distance) train.

Furthermore, to increase the internal validity of the monthly analysis, users who meet at least one of the following criteria during one month are excluded for the respective month in both years.

1. Less than 1 trip in the MVV.
2. Less than 6 trips per week in at least one week during the month.
3. No information on purchase of the D-Ticket.
4. Missing information on start or end locations.

Finally, only trips between September and October in 2022 and 2023 are considered, eliminating seasonal effects. We base our analysis on 92218 trips by 176 unique respondents.

4 Four novel indicators for mobility policy assessment

This paper introduces four novel indicators that are simple yet insightful for assessing the impact of fare policies on individual everyday travel behavior in time and space. These indicators are (a) the generalized cost of travel in fare associations based on GPS trajectories, (b) the travel distance per weekday and fare zone, (c) the activity time per fare zone, and (d) the travel direction per mode and zone of residence.

4.1 Generalized cost of travel in fare associations based on GPS trajectories

The D-Ticket is a governmental subsidy with two goals: countering inflation by reducing consumption prices for Germany's residents, and motivating people to use more sustainable PT instead of cars. Quantifying the monetary savings allows a comparison of governmental subsidy and realized individual savings. Considering the 3 billion in annual subsidies and roughly 13 million users, the subsidy per user amount to 230€ annually or 19€ per month. Using the Mobilität.Leben dataset opens the opportunity for novel and more precise insights. Exploiting the combined information on travel distance, travel duration, geographically traversed zones, ticket ownership, and values of travel time, we can calculate the monthly GCT for each individual and differentiate between PT expenses, MIV expenses, and time spending. Firstly, we expect the owners of the D-Ticket to save 19€ or more on PT and car trips combined compared to before the introduction of the D-Ticket. Secondly, we hypothesize that owners of the D-Ticket increase their PT travel, resulting in a higher expenditure under the unsubsidized pricing regime. Thirdly, we assume that those without a D-Ticket had lower PT spendings than 49€ and do not realize savings on car, PT, or GCT in 2023.

Calculating the ticket price for PT in fare associations like the MVV requires spatial data because the price depends on the traversed geographic area. In our model, PT prices are computed by identifying all districts where the respective trip passed. Each district is assigned a fare zone. The ticket price for PT $PricePT_k$ for each trip k is assigned based on the two most distant fare zones traversed, the most inside zone z_{in} and the most outside zone z_{out}. For every user, all trips that include PT are assigned the respective price.

$$PricePT_k = f(z_{in}, z_{out}) \tag{1}$$

This enhances precision compared to a calculation based on start and end location, especially in fare associations. Knowing the traversed zones for each trip, it is possible to calculate the minimum monthly monetary expenses for PT trips. First, the minimum daily price $DayMinPT_{i,d}$ for user i on the day d is calculated by comparing the sum of all trip prices by each user on each day to the day-ticket $DayTicket_{z_{in},\ z_{out},\ i,\ d}$ that covers all traversed zones. We neglect the possibility of purchasing a daily ticket for parts of the trip and additional single tickets; such a combination is only preferred on rare occasions while increasing the inconvenience; hence, the additional precision does not justify the additional computational effort.

$$DayTicket_{i,\ d} = f(z_{in}, z_{out}) \tag{2}$$

$$DayMinPT_{i,d} = \min\left\{\sum_{k=1}^{y} PricePT_k,\ DayTicket_{i,d}\right\} \tag{3}$$

Secondly, the lowest total monetary cost per month is calculated for each user. Prices for monthly tickets depend on the zones that shall be included. For each user and each month, the cost for each monthly ticket $MonTicket$ - including none - plus all single trips not covered by this ticket is computed. Then, the lowest value of these costs and the sum of all $DayMin$ values is set to be the monthly minimum $MonMinPT_{i,m}$ for user i in month m.

$$MonMinPT_{i,m} = \min\left\{\min\left\{\sum_{d=1}^{31}\left(\sum_{k=1}^{x} PricePT_k\right) + MonTicket_{zIn,zOut}\right\}\forall zIn, zOut; \sum_{d=1}^{31} DayMin_{i,d} \tag{4}$$

Beyond the PT price, the price for each trip $PriceCar_k$ is calculated for car mode, multiplying the trip's car distance by the average price per kilometer. We use values for the most common car in Germany: 55ct (Euro-cents) per kilometer, based on the *VW Golf* according to the latest statistics (ADAC e.V., 01.2024).

$$PriceCar_k = 0,55 * TripCarDistance_k \tag{5}$$

For the cost comparison, the relevant price is selected based on the main mode of transport, either car or PT. Trips with another main mode of transport are considered cost-free and are only considered for the time spending.

Additionally, the monetized time spending is calculated based on the Value of Travel Time Savings (VTTS) derived from the Mobilität.Leben data before the introduction of the D-Ticket (Friederike Beck *et al.*, 2024). Each trip k is assigned a VTTS based on the purpose p of the next stay and the main $mode$. The monetized time expenses $TimeExp_k$ for the same trip are then calculated as follows:

$$TimeExp_k = VTTS_{p,mode} * TripDuration \tag{6}$$

The generalized cost of travel $GCT_{i,m}$ for user i in month m is ultimately calculated as the sum of PT expenses $MonMinPT_{i,m}$, the monthly sum of car trip prices $CarExp_{i,m}$, and time expenses $TimeExp_{i,m}$:

$$GCT_{i,t} = MonMinPT_{i,m} + CarExp_{i,m} + TimeExp_{i,m} \tag{7}$$

4.2 Travel distance per weekday and fare zone

The D-Ticket allows PT trips at zero marginal cost. We hypothesize that owners of the D-Ticket will increase the distance traveled by PT across all zones and decrease the travel distance by car, especially within the most central fare zones. We further assume, that the travel distance for non-owners remains unaltered across all fare zones.

$$TripDist_{i,k} = length(k \cap z) \tag{8}$$

$$Dist_y = \frac{1}{4} \sum_{m=9}^{12} \frac{\sum_{i=1}^{n} \sum_{k=1}^{x} TripDist_{i,k}}{n * dim} \tag{9}$$

The distance per fare zone is calculated as the geographic intersection of trip trajectories with the geographic polygon of each fare zone $length(k \cap z)$. For each trip k we have the distance $TripDist_{i,k}$ within each fare zone. We aggregate the mean distance per zone and day by dividing the total sum of all trip distances in a month m by the number of users n who traveled in that month and the number of days of the respective month. We calculate the period mean $Dist_y$ for $y = 2022$ and $y = 2023$, respectively, as the mean over all four months.

The travel distance per MVV zone illustrates the spatial distribution of travel quantities. It reveals whether a fare innovation shifts travel from one area to another and is relevant for traffic planners to adapt infrastructure or policies accordingly.

4.3 Activity time per fare zone

Acknowledging that trips are made to spend time on activities at the destination, we analyze how the D-Ticket alters the activity time and trip purposes. More specifically, we are interested in the spatial distribution of activity time spent on different purposes. Our first hypothesis is that people who own the D-Ticket spend more leisure time in the central fare zones on workdays and more leisure time in the city center and the most distant fare zones on weekends.Our reasoning is as follows: the city center is especially accessible by PT and many people are already in the city center for work during the week. The D-Ticket enables travel across fare zones without additional cost thus making trips to the distant fare zones more attractive, too. However, the trip duration to these distant destinations makes travel there mostly attractive for longer activities on the weekend. Our second hypothesis is that people with the D-Ticket will spend less time at home. The reasoning is that travelers can afford more out-of-home activities and more trips to the office instead of working from home due to the D-Ticket.

The activity time per zone represents the average time per person spent in each MVV zone; this includes only the time at a destination, not the travel to and from that location.

$$A_{z,\ w,\ p,\ y} = \frac{\sum_i^n a_{i,z,w,\ p,\ y}}{n} \tag{10}$$

$$z \in [M, 1, 2, 3, 5];$$

$$p \in [work - study, leisure, shopping, other, home];$$

$$work - study \in [work, study];$$

$$leisure \in [leisure, sport, eat, familyandfriends];$$

$$shopping \in [shopping, errand];$$

$$other \in [unknown, other, assistance, medicalvisit];$$

$$home \in [home];$$

$$w \in [weekend, workday];$$

$$weekend \in [Saturday, Sunday];$$

$$workday \in [Monday, Tuesday, Wednesday, Thursday, Friday];$$

Thereby $A_{z,\ w,\ p,\ t}$ represents the activity time per fare zone z and type of day w, specifying either weekend or workday, for a purpose p and a specific year y before or after the introduction of the D-Ticket in 2022 and 2023 respectively. Only zones $z \in [M, 1, 2, 3, 5]$ are considered because zones 4 and 6 lack observations. The purposes have been aggregated into 4 groups: "work and study", "leisure", "shopping", and "other"; "home" was considered separately. The activity time $a_{i,\ z,\ w,\ y,\ p}$ is computed per user i in the respective zone with matching purpose and year. We focus on "leisure" and "home" because the results show the highest impact and the data provide most observations for these two purposes. This indicator illustrates how far spatial activity patterns and accessibility of areas change in response to PT fare innovation. Differentiating by activity purposes adds an extra level of analysis and enables more tailored conclusions and interventions.

4.4 Travel direction per mode and zone of residence

One of the D-Ticket's major contributions is to eliminate fare zones for its owners. Hence, they should consider fare zone boundaries irrelevant, and travel across them more often. We assume that most ticket owners are frequent travelers who regularly commute to work by PT and will thus have frequent trips to the city center already before the fare innovation. We hypothesize that travelers with the D-Ticket will increase PT travel to all fare zones outside the fare zone of residence and decrease their car travel in all directions. To examine this issue, we apply the basic concept of origin-destination matrices to fare zones to examine whether the fare innovation alters the travel directions across fare zone boundaries.

$$V_{z,zh} = \frac{1}{4}\sum_{m=9}^{12}\frac{K_{zend=z,m}}{dim * U_{zhome=zh}} \tag{11}$$

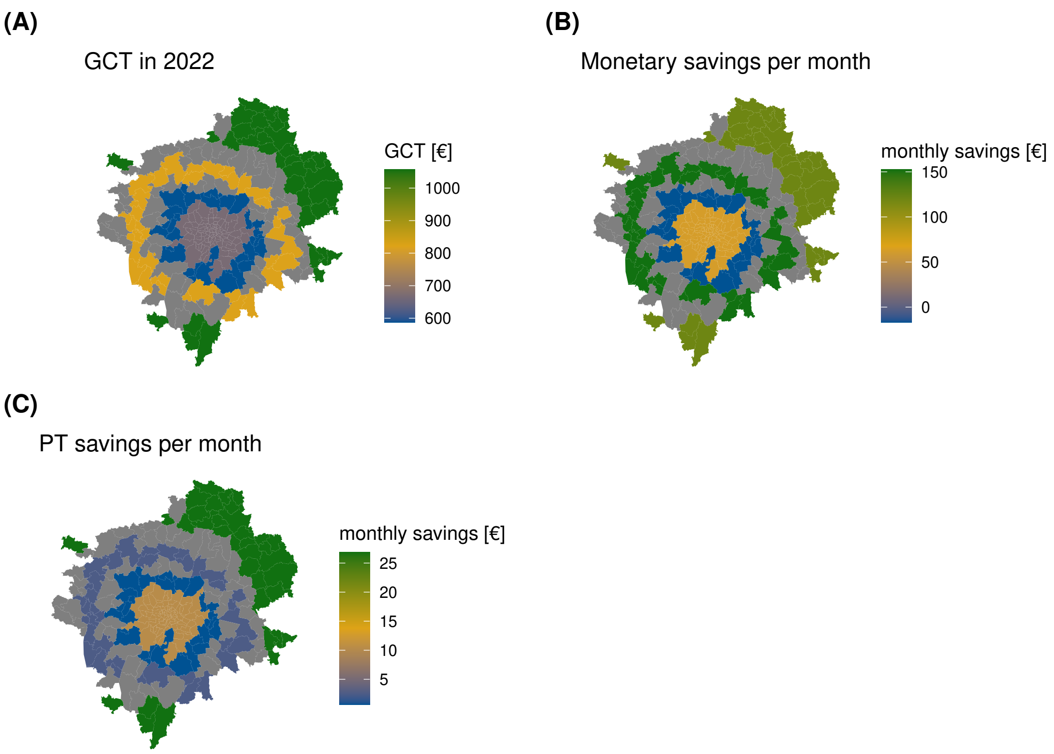
For each user, we calculate the number of trips K that ended in each fare zone $zend = z$ for an entire month m and divide this number by the number of days in month $dim \in [30, 31]$. We then calculate the mean for each fare zone over all users with the same zone of residence $U_{zhome=zh}$ for each month. Ultimately, we calculate the mean over all four months, yielding the average number of trips per user per day for each fare zone of residence zh and trips' end zone z, $V_{z,zh}$. Analyzing these directions for each mode and each fare zone of residence enables spatial equity analysis and allows conclusions on users' mode switch, e.g., substitution of car trips with PT trips.

5 Results

5.1 Monthly travel savings outweigh the subsidy per person

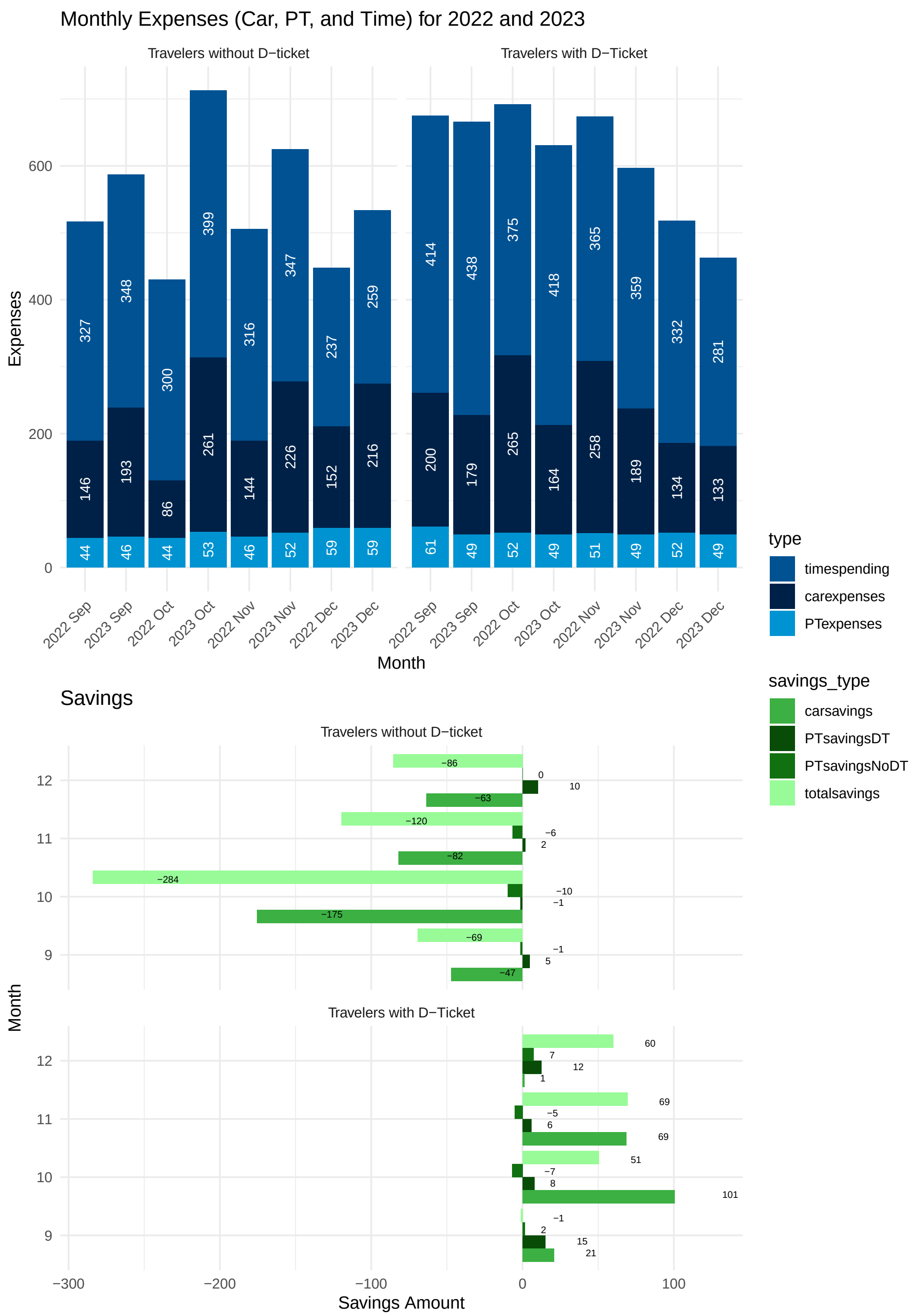
The analysis of GCT and savings of Figure 3 confirms our hypotheses. Firstly, people with the D-Ticket, on average, have higher transport costs than those without. This holds true for PT expenses, car expenses, and GCT. Secondly, GCT for non-owners increases for every month except December, and surprisingly PT expenses without D-Ticket increase in every month of 2023 compared to the same month in 2022. Both groups spend more time traveling, as can be deducted from the GCT savings being consistently lower than the sum of car and PT savings, except for December. Owners save money on PT even when they would have spent more under the old pricing regime, as evident in October and November, indicating that they make more or more expensive trips since the introduction of the D-Ticket. Owners travel less distance by car since the introduction, resulting in average monthly savings on car trips of more than 47€ per person. On average, people save roughly 58€ with the D-Ticket in combined PT and car expenses, by far outweighing the 19€ subsidy per person. However, the savings differ starkly between fare zones, as depicted in Figure 2. The GCT includes time spending, wheras the *monthly savings* in Figure 2 only refers to monetary spending on car and PT or PT ticket prices, respectively. The highest monetary monthly savings per person were accumulated across fare zones 3 and 5, reaching more than 153€ in zone 3. Owners living in zone 1 had no savings in GCT, spending 17€ more on average than before the D-Ticket was introduced. People living in zone M save 62€ per person and month on average if they had the D-Ticket. Notably, the highest savings were realized through reduced car travel costs; savings on PT averaged between 0.60€ in zone 1 and 27€ in zone 5. It is also striking that even in the group of D-Ticket owners, the minimum PT expenses would have been lower than 49€ on average, indicating that some customers would have been cheaper off without the D-Ticket. However, all costs and savings were only calculated for the MVV region, representing everyday mobility. Additional trips outside the fare association will increase the total spending and potentially the savings realized through the D-Ticket. Those without a D-Ticket consistently spend more on PT tickets, car travel, and GCT in 2023 than in 2022.

Figure 2: People who own a D-Ticket benefit from reduced GCT, but the savings differ between fare zones. The gray area is excluded due to the low number of observations.



The data reveal an average monthly spending on mobility, excluding time values, of about 293€ per person before the introduction of the D-Ticket and 234€ after the introduction. This is considerably higher than previous findings from 2021 (DES, 07.07.2021), which might be caused by high inflation in 2022 as well as high price levels in Munich and a high share of high-income households in the data(Loder *et al.*, 2024).

Figure 3: Spending and savings comparing 2023 and 2023 for, PT, car, and time. Positive savings indicate lower spending in 2023 than in 2022. The spendings (top) consider 49€ for all D-Ticket customers, and the savings (bottom) consider the minimum spending based on the realized trips.



5.2 D-Ticket ownership causes opposing trends in the distance per weekday and fare zone

The effects of the D-Ticket on the travel distance by car or PT are straightforward, as visualized in Figure 4 and Figure 5. People who owned the ticket traveled less by car and more by PT, with the highest increase in PT travel in the city center and the most substantial decrease in car travel in the suburbs (zones 1, 2, and 3). The exact opposite effect can be observed for people who do not own the D-Ticket; they travel more by car while the distance by PT remains unchanged; car travel increased most in the city center.

Figure 4: Distances per fare zone in 2022 and changes comparing 2023 to 2022. Respondents with a Deutschlandticket increased PT travel in the city center and decreased car travel. The gray area is excluded due to the low number of observations in fare zone 4.

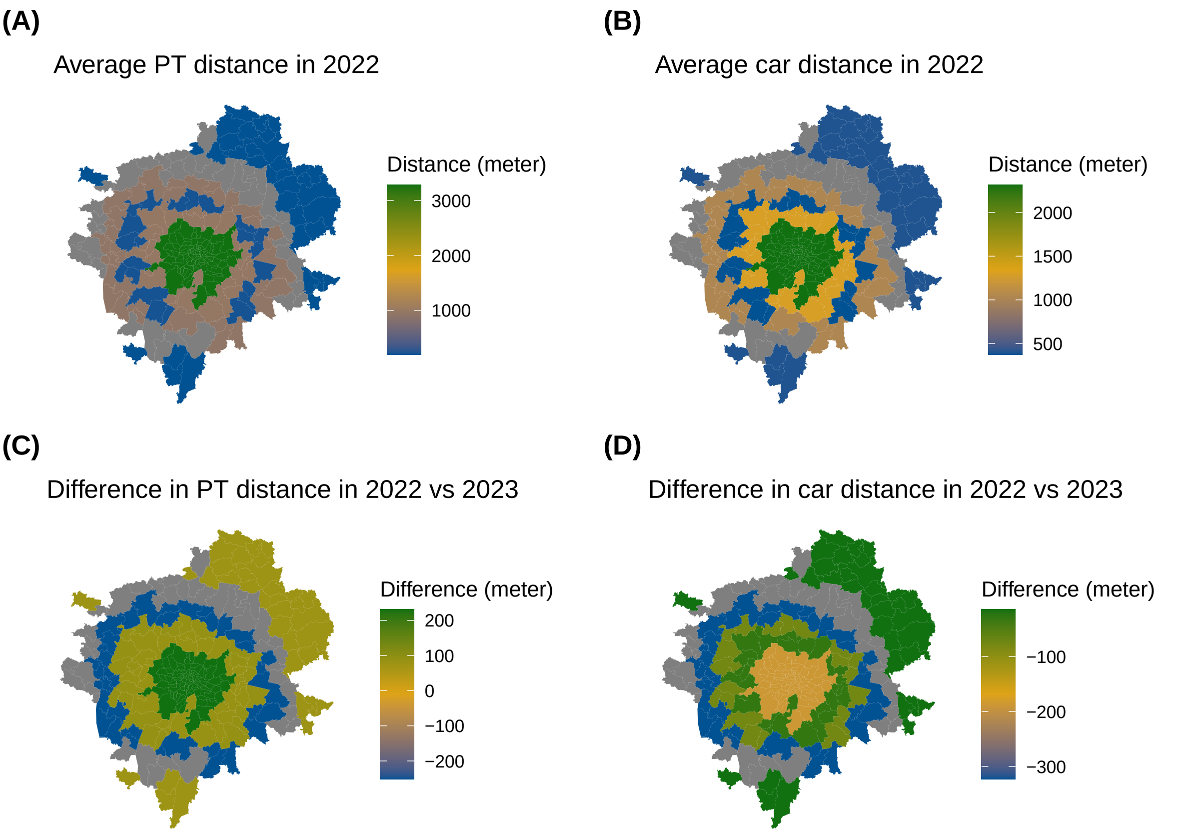
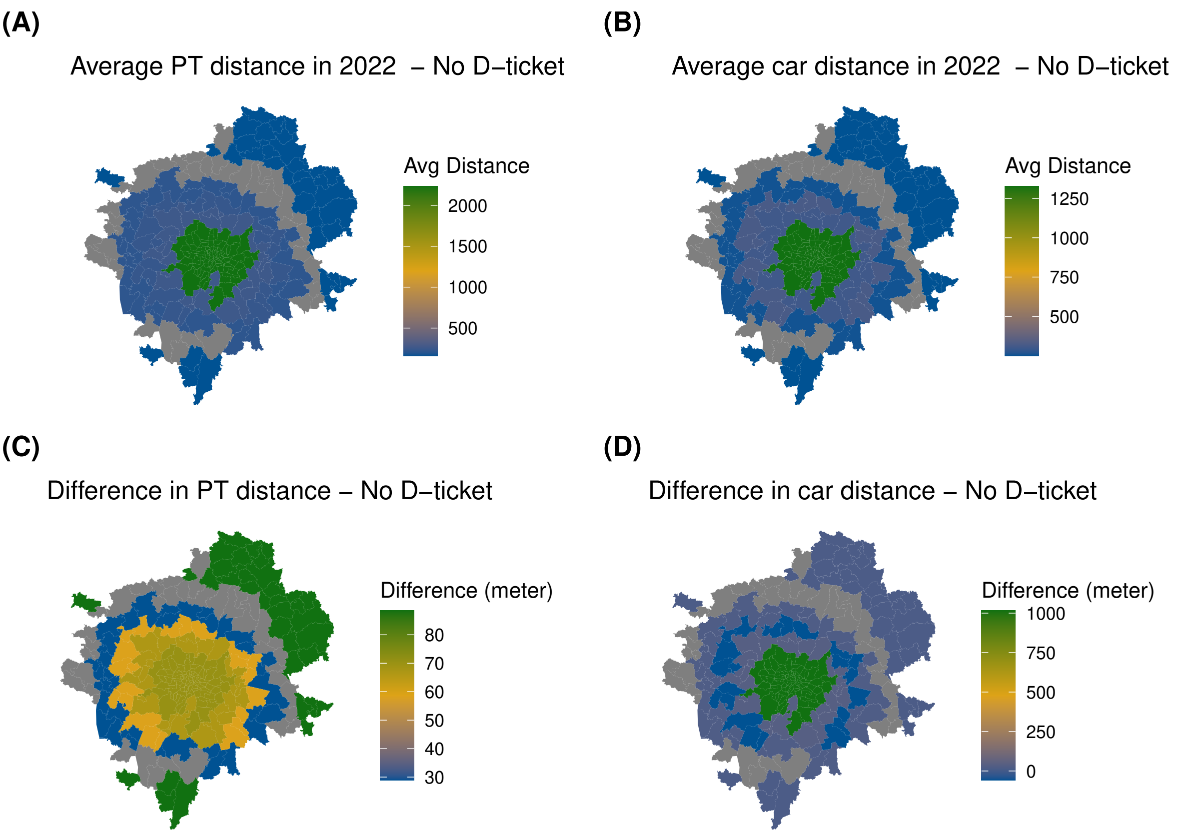


Figure 5: Distances per fare zone in 2022 and changes comparing 2023 to 2022. Respondents without a Deutschlandticket increased car travel and decreased PT travel in the city center. The gray area is excluded due to the low number of observations in fare zone 4.



5.3 Owning the D-Ticket increases accessibility in the suburbs

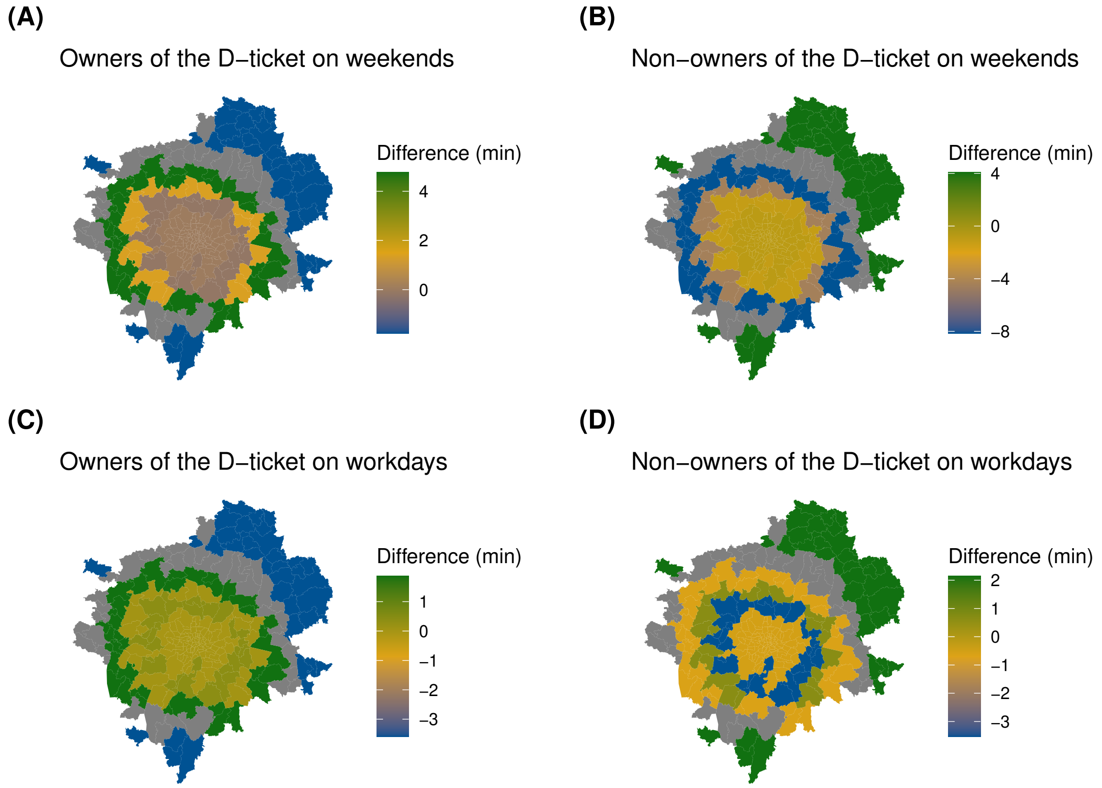
The time spent on leisure activities varies between the period before and after the introduction of the D-Ticket, with a higher variance among those without a D-Ticket. Ticket owners increase their time spent in the city center by one to two minutes per person and day on weekends and four minutes in fare zone 3 per person and day on weekends. Leisure time on workdays increases only slightly in the suburbs and remains constant in the city center. People without D-Ticket increase the time spent in zone 5 by four minutes per person and day while slightly decreasing the time spent in the city center, especially on weekends. This partially contradicts our hypothesis that the D-Ticket motivates ticket owners to spend more leisure time in the more distant fare zones and motivates further research into the causalities behind this observation. Apparently, the Deutschlandticket increases accessibility in the suburbs rather than the distant surroundings. However, the differences between owners and non-owners of the D-Ticket are in line with the hypothesis that the fare innovation increases activity time in the city center on workdays, suggesting that external effects shifted activity times overall between 2022 and 2023. As Figure 7 indicates, people who own the D-Ticket and live in one of the intermediate fare zones 1, 2, or 3 spend more time at home compared to before the introduction, rejecting our second hypothesis on the activity times. The same effect is not observed for people living in the most central or distant fare zones as well as for people who do not own the D-Ticket; those with a central home reveal the highest increase in time spent at home.

Three potential causes may lead to our findings on leisure time. Firstly, distant locations for leisure activities could be less accessible by PT compared to the car, even with reduced ticket expenses. Hence, people might prefer to take the car instead of PT to reach these destinations. Secondly, those who travel to more distant leisure destinations could be cheaper off with occasional single or day tickets than with the D-Ticket; the new ticket might be predominantly appealing to regular commuters and not occasional leisure travelers. Either way, the fare innovation seems to render the suburbs more attractive for leisure activities compared to more distant areas and the city center.

Regarding the time spent at home, three possible explanations support the findings: Firstly, the decreased cost of travel might render trip chaining less necessary and thus increase the number of short stays at home during the day. As this would especially apply to people with short but expensive trips from the city center to the suburbs, this might explain the increase among ticket owners in the suburbs. Secondly, the savings from the D-Ticket might be outweighed by inflation and increased cost of living, hindering people from spending time and money on leisure activities outside the home. Thirdly, the summer of 2022 marked the end of most COVID-19 restrictions in Germany; many people might have been especially motivated to spend time outside the home, and the results show that activity times bounced back to more time spent at home. The same reasoning could be true for an increase in time working from home. A potentially contradicting explanation would be that people spend more time on travel with the Deutschlandticket and thus have less time to spend outside home. More research is necessary to clarify the causality behind our findings.

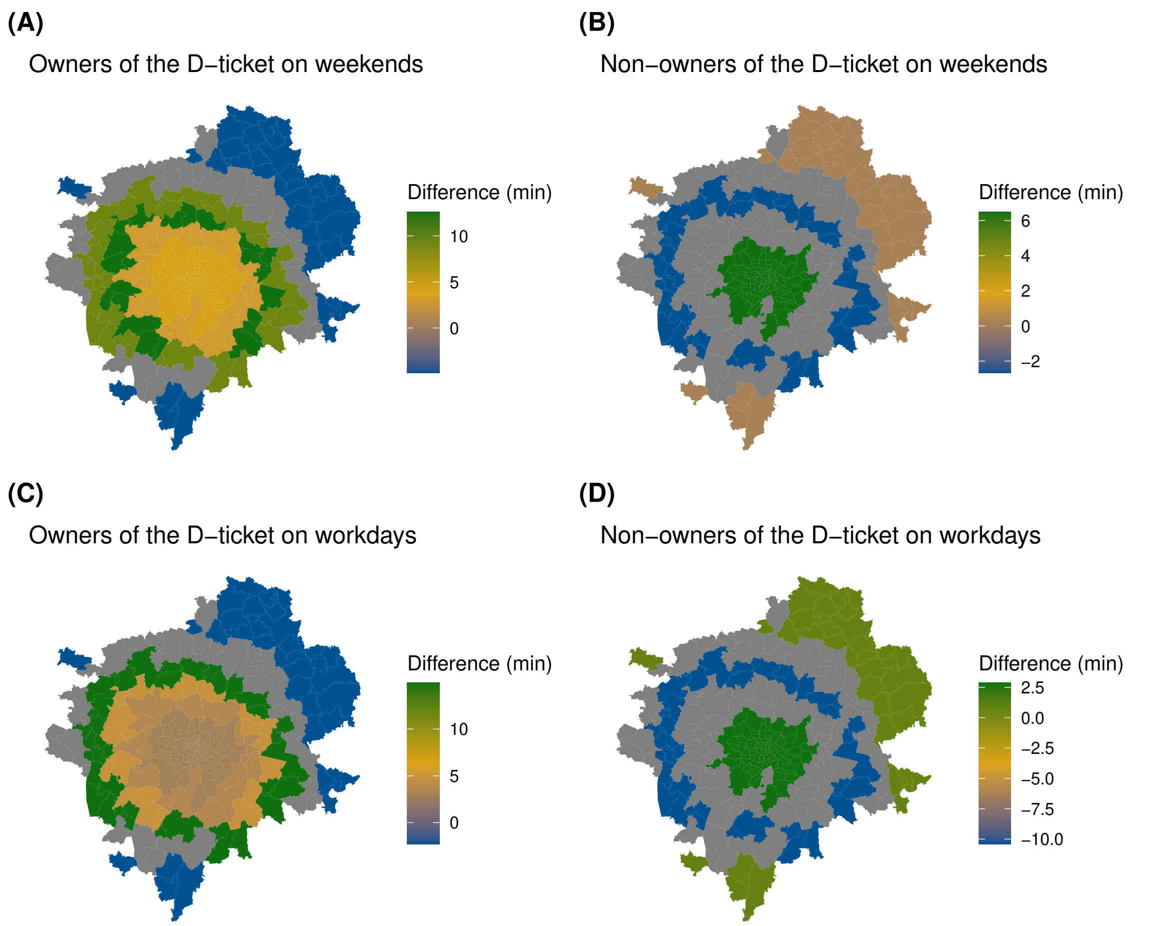
The results suggest that the D-Ticket increases flexibility, especially for people living in the suburbs, allowing more trips to and from home instead of long trip chains. Further studies can verify this finding by analyzing the number of trips and trip chains for people living in different fare zones. The activity time quantifies the accessibility of an area for specific activities during workdays and weekends, respectively. The data can be divided by zones of residence to

Figure 6: Average time spent on leisure in each zone: ticket owners spend more leisure time in the suburbs, non-owners spend more time outside the city. The gray area is excluded due to the low number of observations in fare zone 4.



identify disparities; however, this would go beyond the scope of this study. The results are relevant for spatial equity and dynamic accessibility considerations. Urban and traffic planners may need to consider new activity and travel patterns for specific areas.

Figure 7: Average time spent at home in each zone: ticket owners in the suburbs spend more time at home. The gray area is excluded due to the low number of observations in fare zone 4.



5.4 Travel directions change in an unclear manner

The Travel Directions vary across modes of transport, fare zone of residence, and before and after the introduction of the D-Ticket. Overall, it is evident for each fare zone of residence that most PT trips end in zone M, followed by the residence zone. All other zones account for less than 5% of all PT trips. The distribution of car trips is more diverse; Over 60% of trips by people living in zones M and 2 are directed to zone M. People in zones 1, 3, and 5 have a more diverse distribution, with people in zone 5 directing more than 50% to zone 5. Almost no PT trips occur to fare zones further outside of the city. This remains true after the introduction. Contrary to our hypothesis, there is no clear pattern in how travel directions change after the introduction. While people in zone M only change directions by less than 1.5% and make more trips to zone M, people from zone 3 make 2% less trips to zone M and 4% more trips to zone 3. The findings are represented by Figure 8 and Figure 9.

Figure 8: Distribution of Trip destinations for people living in fare zone 3 (highlighted white).

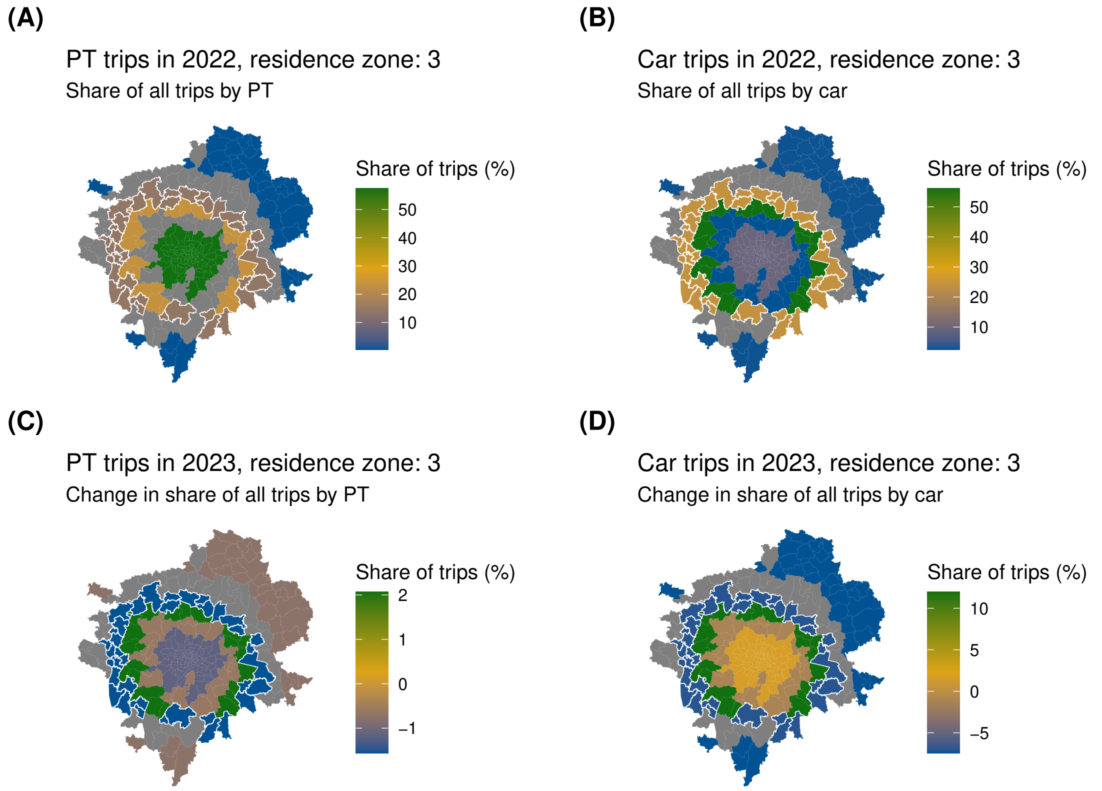
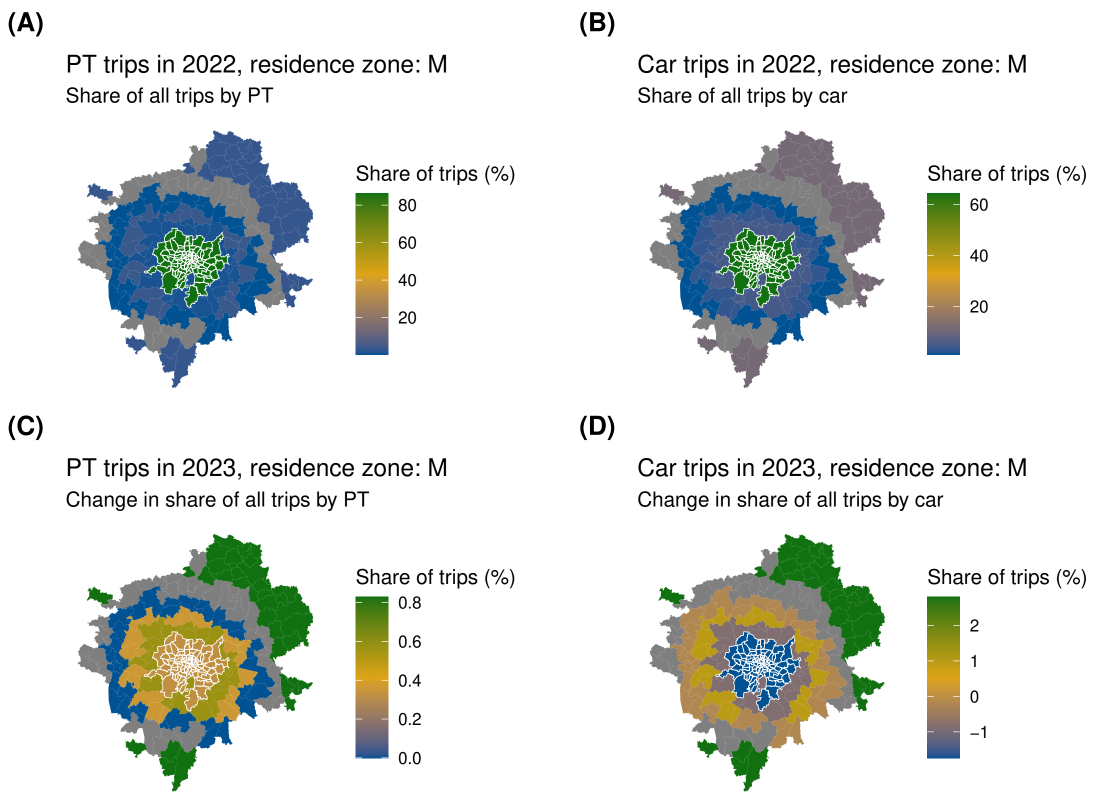


Figure 9: Distribution of Trip destinations for people living in fare zone M (highlighted white).



6 Discussion

Despite several studies addressing individuals' position in time and space individually (Follmer and Treutlein, 2023; Gaus *et al.*, 2023; Bigi *et al.*, 2023), combining both dimensions is considered a promising research avenue (Lu *et al.*, 2024). We addressed this gap with four novel indicators drawing upon the detailed information on the Munich metropolitan region provided by the 20-month semi-passive tracking panel Mobilität.Leben. The considered fare association, the MVV, is structured in a central zone M, covering the city center, intermediate zones 1 through 3, encompassing the suburbs, and the more distant zones 4 through 6. We omitted zones 6 and 4 in our analysis due to a lack of responses from these areas.

Monetary savings from the Deutschlandticket exceed the subsidy per person by far, averaging almost 72€ for ticket owners compared to a cost increase of 100€ among non-owners. This extreme increase is probably cause by very low sosts in October 2022 and should be verified with a more representative sample. The subsidy, anyways, is thus highly cost-effective in reducing the financial burden of the past years with high inflation (Rozynek *et al.*, 2023; Andor *et al.*, 2023). The savings also outweigh the loss on additional travel time, which had already been identified in previous studies (Verband Deutscher Verkehrsunternehmen e. V. *et al.*, 16.12.2022; O2 Telefónica, 2023). The spending and savings are spatially diverse, with people in the most distant zones realizing the highest benefit; the indicator thus allows further differentiation of who gains how much from the fare innovation (Andor *et al.*, 2023). Even excluding any travel beyond the borders of the fare association MVV, many people without the Deutschlandticket would have financially benefited from buying the ticket, verifying previous findings (Verband Deutscher Verkehrsunternehmen e. V. *et al.*, 16.12.2022; O2 Telefónica, 2023; Loder *et al.*, 2024). Some people who own the Deutschlandticket would have spent less than 49€ on everyday mobility in the respective month with another ticket, but potential travel beyond the scope of the MVV could still render the ticket worthwhile. In the context of an announced price increase for the Deutschlandticket in 2025 (mdr, 09.07.2024), detailed insights into the individual travel costs indicate which travelers would still benefit or lose how much from specific prices, based on previous and current travel behavior (Zhao and Zhang, 2019).

Travel distance increases for public transport and decreases for cars among owners of the Deutschlandticket since the ticket was introduced; travel distances with public transport increase overall, especially throughout the city center, whereas car distance is predominantly reduced in the suburbs. Non-owners show the opposite development, traveling more by car and in the city center but less with public transport.

Activity time at home increases for ticket owners in the suburbs after the fare innovation. Furthermore, the Deutschlandticket makes the city center more accessible for ticket owners' leisure on weekends and the suburbs more accessible during workdays. More distant destinations around Munich have experienced an even more substantial increase among non-owners since the introduction. These results add a spatial dimension to previous findings of changing activity patterns (Bull *et al.*, 2021) and trip purposes after public transport fare innovations (Gaus *et al.*, 2023; Verband Deutscher Verkehrsunternehmen e. V. *et al.*, 16.12.2022). The findings enrich spatial considerations of equity and accessibility by comparing the impact of fare innovations across fare zones or areas of residence (Zhao and Zhang, 2019; Tiznado-Aitken *et al.*, 2021) as well as times of the week, hinting at the dynamic component of accessibility (Ryan *et al.*, 2023). Addressing activity times at different locations, the primary reason for travel (Mokhtarian and Salomon, 2001), in the assessment of fare innovation or, in fact, mobility policy interventions in general, is long overdue.

Our study found that directions of public transport trips by people who own a Deutschlandticket overwhelmingly lead to zone M or their residence zone. Car trips are more distributed and less focused on the city center. Despite abolishing fare zones for its owners, the new ticket does not systematically change travel directions. With increasing trip numbers (Loder *et al.*, 2024; Verband Deutscher Verkehrsunternehmen e. V. *et al.*, 16.12.2022; O2 Telefónica, 2023) and constant trip shares, the total number of trips across fare zones also increases with the Deutschlandticket. However, the effects are only marginal and will need further verification in future studies. The travel directions add a new level of analysis that is especially important in European public transport fare structures based on fare associations. The indicator can be adapted for geographical travel directions. Especially for innovative fare structure approaches such as the *homezone* (Weigele *et al.*, 2021) or in the context of MaaS (Hörcher and Graham, 2021; Arslan *et al.*, 2016), empirical data on the geographic area of travel provide valuable insights.

Overall, the Deutschlandticket makes the suburbs more accessible by public transport. Financially, the gains increase with distance from the city center and outweigh governmental subsidies per person. The ticket motivates owners to shift from car to public transport, especially in the city center, increasing sustainability (Krämer and Mietzsch, 2024; Follmer and Treutlein, 2023).

The study acknowledges limitations, mostly due to the novelty of the indicators not considered during data collection. Firstly, this resulted in incomplete data and an uneven spatial distribution of observations. Responses for zone 4 were specifically sparse. Future studies should recruit more representative data and more spatially distributed respondents. Secondly, car travel expenses were estimated using average costs per km, giving an under-complex estimate for actual monthly expenses. By collecting data on the car model, these estimates can be optimized. Thirdly, our calculation of public transport costs does not reflect if the user purchased the optimal ticket but estimates optimal costs based on realized trips. In the future, the ownership of specific tickets should be collected to increase the precision of the actual cost. While the minimal cost considered in our study would not differ, higher precision would benefit the calculation of the Value of Travel Time Savings and the monetary value attributed to the flexibility and ease of use of seasonal tickets. Fourthly, not every trip in our data has a (correctly) assigned trip purpose, limiting the validity of activity time results. While the technology to detect trip purposes correctly improves, respondents could be incentivized to correct trip purposes in the smartphone app.

7 Conclusion

This paper explored how the Deutschlandticket changes the spatial and temporal dimensions of everyday mobility by proposing four novel indicators in this paper: (a) the generalized cost of travel in fare associations based on GPS trajectories, (b) the travel distance per weekday and fare zone, (c) the activity time per fare zone, and (d) the travel direction per mode and zone of residence.

The presented results underscore the importance of an integrated perspective on otherwise separately addressed issues (Calastri *et al.*, 2020) of spatial and temporal dimensions of travel. The impact of public transport fare innovations varies across fare zones, weekdays, and times of year. The Deutschlandticket motivated a shift from car to public transport in the city center, increased trip flexibility in the suburbs, and generated monetary savings far beyond the governmental subsidy per person.

Further research can delve deeper into the spatial and temporal dimensions of travel behavior provided by the provided novel indicators and the associated equity considerations, as well as travel behavior provided by the novel indicators. An interesting next step would be an analysis of external travel costs (Schröder *et al.*, 2023) based on revealed travel data in a high spatial and temporal resolution. Another intriguing approach would be to exploit the sociodemographic dimension of the data and examine equity across gender or income. Beyond accessibility and equity, the indicators can be used to better estimate transport parameters. This paper is the first to quantify the monetary impact of a major fare innovation in a fare association based on multi-month smartphone-based tracking data. The results can be used to derive more precise estimates of travel demand and the value of travel time. In future and ongoing projects we incorporate these indicators already in the study design.

In conclusion, the four novel indicators generate crucial insights into the impact of the Deutschlandticket on people living in areas of different centrality and successfully contribute to the methodology for public transport fare innovation assessment; in particular, complex fare structures like fare associations can be precisely analyzed. The indicators provide relevant insights for researchers, planners, and policymakers regarding budget constraints and the UN SDGs (United Nations Department of Economic and Social Affairs, 2024) on accessibility, sustainability, and equity.

8 Acknowledgments

The authors would like to thank the TUM Think Tank at the Munich School of Politics and Public Policy for its support. GPT-4 assisted in debugging the R code, creating LaTeX tables, and making language edits.

9 Authors Contribution

The authors confirm contribution to the paper as follows: study conception and design: Martin Schlett; data collection: Allister Loder, zzz; analysis and interpretation of results: Martin Schlett; draft manuscript preparation: Martin Schlett; Supervision: Allister Loder. All authors reviewed the results and approved the final version of the manuscript.

10 Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

11 Funding

The authors disclosed receipt of the following financial support for the data collection of this article: This research was supported by TUM Think Tank.

12 References

(07.07.2021) Pressemitteilung Nr. N 045 vom 7. Juli 2021, https://www.destatis.de/DE/Presse/Pressemitteilungen/2021/07/PD21_N045_639.html.

(09.07.2024) Verkehrsminister: Preis für Deutschlandticket soll 2025 steigen, https://www.mdr.de/nachrichten/deutschland/politik/deutschlandticket-preis-erhoehung-teurer-100.html.

ADAC e.V. (01.2024) ADAC Autokosten Herbst/Winter 2024: Kostenübersicht für 1.249 aktuelle Neuwagen-Modelle, https://assets.adac.de/Autodatenbank/Autokosten/autokostenuebersicht.pdf.

Aguiléra, A. and V. Boutueil (2019) *Urban mobility and the smartphone: Transportation, travel behavior and public policy*, Elsevier, Amsterdam, ISBN 9780128126486.

Andor, M. A., F. Dehos, K. Gillingham, S. Hansteen and L. Tomberg (2023) *Public transport pricing: An evaluation of the 9-Euro Ticket and an alternative policy proposal*, vol. #1045 of *Ruhr economic papers*, RWI - Leibniz-Institut für Wirtschaftsforschung, Essen, Germany, ISBN 9783969732144.

Arslan, S., V. Demirel and İ. Kuru (2016) A Public Transport Fare Collection System with Smart Phone Based NFC Interface, *International Journal of Electronics and Electrical Engineering*, 258–262. DOI 10.18178/ijeee.4.3.258-262.

Baum, H. J. (1973) Free Public Transport, *Journal of Transport Economics and Policy*, **vol. 7** (no. 1) 3–19.

Bertolini, L. (2020) From “streets for traffic” to “streets for people”: can street experiments transform urban mobility?, *Transport reviews*, **40** (6) 734–753. DOI 10.1080/01441647.2020.1761907.

Bigi, F., N. Schwemmle and F. Viti (2023) Evaluating the impact of Free Public Transport using agent-based modeling: the case-study of Luxembourg, https://www.researchgate.net/publication/374008353_Evaluating_the_impact_of_Free_Public_Transport_using_agent-based_modeling_the_case-study_of_Luxembourg.

Buehler, R. and J. Pucher (2012) Demand for Public Transport in Germany and the USA: An Analysis of Rider Characteristics, *Transport reviews*, **32** (5) 541–567. DOI 10.1080/01441647.2012.707695.

Buehler, R., J. Pucher and O. Dümmler (2019) Verkehrsverbund: The evolution and spread of fully integrated regional public transport in Germany, Austria, and Switzerland, *International Journal of Sustainable Transportation*, **13** (1) 36–50. DOI 10.1080/15568318.2018.1431821.

Bull, O., J. C. Muñoz and H. E. Silva (2021) The impact of fare-free public transport on travel behavior: Evidence from a randomized controlled trial, *Regional Science and Urban Economics*, **86**, 103616. DOI 10.1016/j.regsciurbeco.2020.103616.

Busch-Geertsema, A., M. Lanzendorf and N. Klinner (2021) Making public transport irresistible? The introduction of a free public transport ticket for state employees and its effects on mode use, *Transport policy*, **106**, 249–261. DOI 10.1016/j.tranpol.2021.04.007.

Calastri, C., R. Crastes dit Sourd and S. Hess (2020) We want it all: experiences from a survey seeking to capture social network structures, lifetime events and short-term travel and activity planning, *Transportation*, **47** (1) 175–201. DOI 10.1007/s11116-018-9858-7.

Cats, O., Y. O. Susilo and T. Reimal (2017) The prospects of fare-free public transport: evidence from Tallinn, *Transportation*, **44** (5) 1083–1104. DOI 10.1007/s11116-016-9695-5.

Die Bundesregierung (2023) Bund finanziert Deutschlandticket mit 1,5 Milliarden Euro: Änderung des Regionalisierungsgesetzes, `https://www.bundesregierung.de/breg-de/aktuelles/regionalisierungsgesetz-deutschlandticket-2161096`.

Die Bundesregierung (2024a) 9-Euro-Ticket 52 Millionen Mal verkauft: Fragen und Antworten, `https://www.bundesregierung.de/breg-de/aktuelles/faq-9-euro-ticket-2028756`.

Die Bundesregierung (2024b) Deutschlandticket Fragen und Antworten, `https://www.bundesregierung.de/breg-de/aktuelles/deutschlandticket-2134074`.

Dutra, A. (2019) The Present and the Future of Fare-Free Public Transport and Sustainable Public Transport: The Cases of Avesta and Tallinn and The Visions for Luxembourg and Uppsala, Master thesis, Uppsala University, Uppsala.

Fajardo-Magraner, F., J. Salom-Carrasco and M. D. Pitarch-Garrido (2023) Space-time Models and Personal Accessibility to Educational Facilities. Case Study of Space-time Accessibility to Schools in the City of Valencia, *Applied Spatial Analysis and Policy*, **16** (4) 1395–1415. DOI 10.1007/s12061-023-09510-5.

Follmer, R. and J. Treutlein (2023) KlimaTicket Report 2022: Methode und Ergebnisse der wissenschaftlichen Begleitforschung und Nachfrageerhebung zum KlimaTicket Österreich,, `https://www.bmk.gv.at/themen/mobilitaet/1-2-3-ticket/publikationen/klimaticket-report-2022.html`.

Friederike Beck, Santiago Álvarez-Ossorio Martínez, Klaus Bogenberger and Allister Loder (2024) Analyzing the 9-Euro-Ticket Mode Choice Impact Using GPS Panel Data and Discrete Choice Models: First Insights.

Gallo, M. and M. Marinelli (2020) Sustainable Mobility: A Review of Possible Actions and Policies, *Sustainability*, **12** (18) 7499. DOI 10.3390/su12187499.

Gaus, D., N. Murray and H. Link (2023) 9-Euro-Ticket: Niedrigere Preise allein stärken Alltagsmobilität mit öffentlichen Verkehrsmitteln nicht.

Gillard, M., W. Kębłowski, K. Boussauw and V. van Acker (2024) “I always say, it’s the icing on the cake”: the discursive production of fare-free public transport in Luxembourg, *Urban Geography*, 1–23. DOI 10.1080/02723638.2024.2412918.

Hackl, A. (2018) Mobility equity in a globalized world: Reducing inequalities in the sustainable development agenda, *World Development*, **112**, 150–162. DOI 10.1016/j.worlddev.2018.08.005.

Hörcher, D. and D. Graham (2021) Pricing and Efficient Public Transport Supply in a Mobility as a Service Context: Discussion Papers.

Kamargianni, M., W. Li, M. Matyas and A. Schäfer (2016) A Critical Review of New Mobility Services for Urban Transport, *Transportation Research Procedia*, **14**, 3294–3303. DOI 10.1016/j.trpro.2016.05.277.

Kebłowski, W., T. Tuvikene, T. Pikner and J. S. Jauhiainen (2019) Towards an urban political geography of transport: Unpacking the political and scalar dynamics of fare-free public transport in Tallinn, Estonia, *Environment and Planning C: Politics and Space*, **37** (6) 967–984. DOI 10.1177/2399654418821107.

Khan, N. A., M. A. Habib and S. Jamal (2020) Effects of smartphone application usage on mobility choices, *Transportation Research Part A: Policy and Practice*, **132**, 932–947. DOI 10.1016/j.tra.2019.12.024.

Krämer, A. (2024) *New Mobility – vom 9-Euro-Ticket zur Verkehrswende?*, Springer Fachmedien Wiesbaden, Wiesbaden, ISBN 978-3-658-44034-3.

Krämer, A. and A. Korbutt (2022) Das Deutschlandticket aus Sicht des hvv und in der bundesweiten Betrachtung, `https://exeo-consulting.com/pdf/exeo_Deutschlandticket%20im%20hvv%20und%20bundesweit_2023.pdf`.

Krämer, A. and O. Mietzsch (2024) Zukunft Deutschlandticket: Verkehrswende, Finanzierung und wohlfahrtsökonomische Wirkung, *Wirtschaftsdienst*, **104** (9) 636–643.

Kwan, M.-P. (1998) Space–Time and Integral Measures of Individual Accessibility: A Comparative Analysis Using a Point–based Framework, *Geographical Analysis*, **30** (3) 191–216. DOI 10.1111/j.1538-4632.1998.tb00396.x.

Larsen, O. I. and J. Rekdal (2010) Treatment of seasonal tickets for public transport in estimation and application of mode/destination choice models, *Transportation*, **37** (3) 573–581. DOI 10.1007/s11116-009-9256-2.

Loder, A. (2024) Recent Public Transport Fare Policy Innovations in germany: Insights from a Year-ong GPS-Tracking Study, `https://mediatum.ub.tum.de/doc/1744109/document.pdf`.

Loder, A., F. Cantner, L. Adenaw, N. Nachtigall, D. Ziegler, F. Gotzler, M. B. Siewert, S. Wurster, S. Goerg, M. Lienkamp and K. Bogenberger (2024) Observing Germany's nationwide public transport fare policy experiment "9-Euro-Ticket" – Empirical findings from a panel study, *Case Studies on Transport Policy*, **15**, 101148. DOI 10.1016/j.cstp.2024.101148.

Loder, A., F. Cantner, V. Dahmen and K. Bogenberger (2023) The Mobilität.Leben Study: a Year-Long Mobility-Tracking Panel.

Lu, Q.-L., V. Mahajan, C. Lyu and C. Antoniou (2024) Analyzing the impact of fare-free public transport policies on crowding patterns at stations using crowdsensing data, *Transportation Research Part A: Policy and Practice*, **179**, 103944. DOI 10.1016/j.tra.2023.103944.

Mokhtarian, P. and I. Salomon (2001) How derived is the demand for travel? Some conceptual and measurement considerations, *Transportation Research Part A: Policy and Practice*, **35**, 695–719. DOI 10.1016/S0965-8564(00)00013-6.

Molloy, J. (2021) Undertaking mobility field experiments using GPS tracking, Ph.D. Thesis, ETH Zurich.

Molloy, J., A. Castro, T. Götschi, B. Schoeman, C. Tchervenkov, U. Tomic, B. Hintermann and K. W. Axhausen (2022) The MOBIS dataset: a large GPS dataset of mobility behaviour in Switzerland, *Transportation*, 1–25. DOI 10.1007/s11116-022-10299-4.

Molloy, J., T. Schatzmann, B. Schoeman, C. Tchervenkov, B. Hintermann and K. W. Axhausen

(2021a) Observed impacts of the Covid-19 first wave on travel behaviour in Switzerland based on a large GPS panel, *Transport policy*, **104**, 43–51. DOI 10.1016/j.tranpol.2021.01.009.

Molloy, J., C. Tchervenkov and K. W. Axhausen (2021b) Estimating the external costs of travel on GPS tracks, *Transportation Research Part D: Transport and Environment*, **95** (1) 102842. DOI 10.1016/j.trd.2021.102842.

Mouter, N., P. Koster and T. Dekker (2021) Contrasting the recommendations of participatory value evaluation and cost-benefit analysis in the context of urban mobility investments, *Transportation Research Part A: Policy and Practice*, **144**, 54–73. DOI 10.1016/j.tra.2020.12.008.

Münchener Verkehrs- und Tarifverbund (2021a) Basisdaten Mobilität im Landkreis München: Aktualisierte Fassung, `https://www.mvv-muenchen.de/fileadmin/mediapool/07-Ueber_den_MVV/02-Dokumente/MVV_in_Zahlen/Desktopdruck_M_Nov_22_Basisdaten_komplett.pdf`.

Münchener Verkehrs- und Tarifverbund (2021b) MVV-Preise ab 12.12.2021: IsarCards, `https://www.mvv-muenchen.de/fileadmin/mediapool/04-Tickets/02-Dokumente/2022_Preisuebersicht_WEB_IsarCards.pdf`.

Neutens, T., M. Delafontaine, D. M. Scott and P. de Maeyer (2012) An analysis of day-to-day variations in individual space–time accessibility, *Journal of Transport Geography*, **23**, 81–91. DOI 10.1016/j.jtrangeo.2012.04.001.

O2 Telefónica (2023) Das Deutschlandticket bewirkt deutlich mehr Pendel- und Wochenendfahrten: O2 Telefónica Mobility Monitor – Ausgabe 3:, `https://www.telefonica.de/news/corporate/2023/07/o2-telefonica-mobility-monitor-ausgabe-3-das-deutschlandticket-bewirkt- deutlich-mehr-pendel-und-wochenendfahrten.html`.

Oviedo, D., C. Cavoli, C. Levy, B. Koroma, J. Macarthy, O. Sabogal, F. Arroyo and P. Jones (2022) Accessibility and sustainable mobility transitions in Africa: Insights from Freetown, *Journal of Transport Geography*, **105**, 103464. DOI 10.1016/j.jtrangeo.2022.103464.

Pucher, J. and S. Kurth (1995) Verkehrsverbund: the success of regional public transport in Germany, Austria and Switzerland, *Transport policy*, **2** (4) 279–291. DOI 10.1016/0967-070X(95)00022-I.

Rozynek, C., G. Mattioli and C. Aberle (2023) Was darf die ÖPNV-Nutzung im Kontext sozialer Teilhabe kosten? : Ideen für Indikatoren der ÖPNV-Erschwinglichkeit.

Rubensson, I., Y. Susilo and O. Cats (2020) Is flat fare fair? Equity impact of fare scheme change, *Transport policy*, **91**, 48–58. DOI 10.1016/j.tranpol.2020.03.013.

Ryan, J., R. H. Pereira and M. Andersson (2023) Accessibility and space-time differences in when and how different groups (choose to) travel, *Journal of Transport Geography*, **111**, 103665. DOI 10.1016/j.jtrangeo.2023.103665.

Schelewsky, M., H. Jonuschat, B. Bock and K. Stephan (2014) *Smartphones unterstützen die Mobilitätsforschung*, Springer Fachmedien Wiesbaden, Wiesbaden, ISBN 978-3-658-01847-4.

Schönau, M. (2016) GPS-basierte Studien zur Analyse der nachhaltigen urbanen Individualmobilität, Ph.D. Thesis, Universität Ulm.

Schröder, D., L. Kirn, J. Kinigadner, A. Loder, P. Blum, Y. Xu and M. Lienkamp (2023) Ending the myth of mobility at zero costs: An external cost analysis, *Research in Transportation Economics*, **97**, 101246. DOI 10.1016/j.retrec.2022.101246.

Silver, K., A. Lopes, D. Vale and N. M. Da Costa (2023) The inequality effects of public transport fare: The case of Lisbon's fare reform, *Journal of Transport Geography*, **112**, 103685. DOI 10.1016/j.jtrangeo.2023.103685.

Simma, A. and K. Axhausen (2001) Structures of commitment in mode use: a comparison of Switzerland, Germany and Great Britain, *Transport policy*, **8** (4) 279–288. DOI 10.1016/S0967-070X(01)00023-3.

Stadtverwaltung Templin (2019) Information: Fahrscheinfreier Stadtverkehr, `https://www.templin.de/wp-content/uploads/2023/07/Fahrscheinfreier-Stadtverkehr-Stadt-Templin_2020.pdf`.

Storchmann, K. (2003) Externalities by Automobiles and Fare-Free Transit in Germany - A Paradigm Shift?, *Journal of Public Transportation*.

Suckow, Silvio, George and Sarah (2023) Das Neun-Euro-Ticket: Ein Experiment mit Folgen? Repräsentative Panel-Daten, Überblicksstudie und Debattenbeitrag: WZB Discussion Paper, `https://hdl.handle.net/10419/279780`.

Tiznado-Aitken, I., J. C. Muñoz and R. Hurtubia (2021) Who gains in a distance-based public transport fare scheme? Accessibility, urban form, and equity implications in Santiago, Chile, in *Urban Form and Accessibility*, 265–288, Elsevier, ISBN 9780128198223.

United Nations Department of Economic and Social Affairs (2024) The 17 Goals, https://sdgs.un.org/goals.

Verband Deutscher Verkehrsunternehmen e. V., Deutsche Bahn AG and DB Regio AG (16.12.2022) Abschlussbericht zur bundesweiten Marktforschung: Deutschland steigt ein, https://www.vdv.de/bilanz-9-euro-ticket.aspx.

Victoria Dahmen, Santiago Álvarez-Ossorio Martinez, Allister Loder and Klaus Bogenberger (2023) Making Large-Scale Semi-Passive GPS Travel Diaries Valuable: a Quality Enhancement Method.

Wagner, D. P. (15.09.1997) Lexington Area Travel Data Collection Test: GPS for Personal Surveys, Final Report for OHIM, OTA, and FHWA, https://www.fhwa.dot.gov/ohim/lextrav.pdf.

Wallimann, H. (12.01.2024) Austria's KlimaTicket: Assessing the short-term impact of a cheap nationwide travel pass on demand, http://arxiv.org/pdf/2401.06835v2.

Weibel, C., L. Dang and W. von Arx (2024) Increasing public transport revenue or intensifying cannibalization: The effects of introducing a new tariff option in addition to pay-per-use and flat rate options, *Research in Transportation Business & Management*, **54**, 101129. DOI 10.1016/j.rtbm.2024.101129.

Weigele, S., A. Fechner, B. Bock and S. Herrmann (2021) Homezone – innovatives E-Tarifkonzept für den ÖPNV, *Nahverkehr*, **39** (12).

Zhao, P. and Y. Zhang (2019) The effects of metro fare increase on transport equity: New evidence from Beijing, *Transport policy*, **74**, 73–83. DOI 10.1016/j.tranpol.2018.11.009.