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

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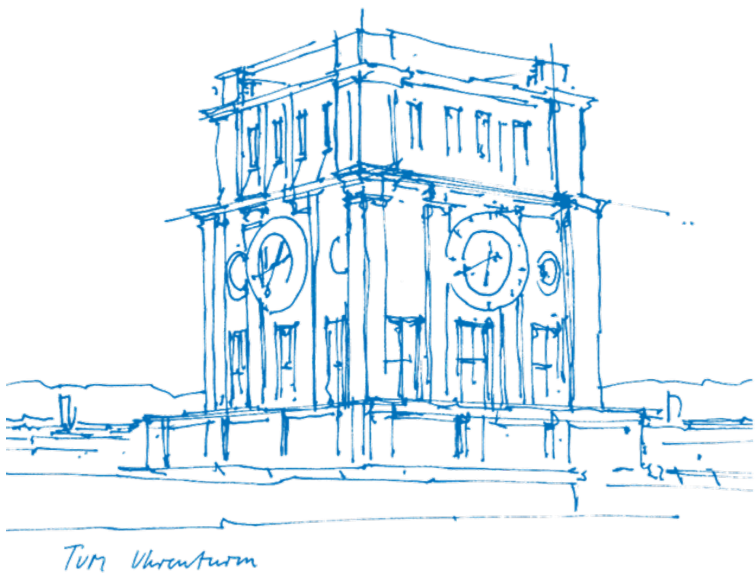

Public Transport through Time and Space: Novel Indicators for Mobility Policy Assessment

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Abstract

Policymakers face new or increasingly pressing constraints like climate change, land consumption, and inequality. Implemented measures such as pricing are not novel but increasingly tailored towards public transport and active mobility instead of cars, including the redistribution of urban space for increased accessibility and equity. In times of severe budget constraints on businesses and governments across the globe, assessing the impact of public transport fare policy decisions, especially those costly for the government, operator, or user, is crucial. However, until now, studies analyzing the impact of fare policies have not exploited the potential of novel smartphone-based tracking data. This paper closes the gap by introducing four novel indicators that are simple yet insightful for assessing the impact of public transport PT fare innovations on individual everyday travel behavior: (a) the activity time per fare zone, (b) the monetary travel cost in fare associations based on GPS trajectories, (c) the travel direction per mode and zone of residence, and (d) the travel time per time of day, weekday, and fare zone. Their relevance for assessing PT fare innovations and possible modifications of the indicators are discussed. Based on multi-month semi-passive smartphone-based tracking data, the results show that PT fare innovation impact varies across fare zones, time of day, and time of year. The paper contributes to assessing the Deutschlandticket and expands scientific methods for assessing public transport fare innovations.

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1 Introduction

Recent changes in society and technological innovation have impacted mobility. Working from home and videoconferencing changed the need for daily commutes and business trips Faber *et al.* (2023); Wöhner (2022); Kolarova *et al.* (2021). Urbanization contributed to the increasing divide between urban and rural populations while concentrating the public and scientific debate on urban mobility Camarero and Oliva (2019). Mobility policy goals focus more on climate neutrality, accessibility, and mobility justice. Cost efficiency and political feasibility remain important. Societies across the globe try to achieve the United Nations Sustainable Development Goals (UN SDGs) United Nations Department of Economic and Social Affairs (2024). With multiple of these tied to mobility policy, climate neutrality, equity, and resilient mobility infrastructure systems are 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 seasonal 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, it is crucial to assess the impact of fare policy decisions, especially for costly PT fare innovations.

Literature impact assessment of PT fare innovations reaches back decades, primarily using established indicators like trip numbers, distances, and travel times 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). Tracking data covering a period before and after the introduction of the Deutschlandticket (DT) Loder *et al.* (2023) - a low-cost travel passfor PT in Germany described below - bears potential for further analysis of combined temporal and spatial dimensions. This potential extends to activity times at different locations, which is the primary motivation for mobility Mokhtarian and Salomon (2001). This paper contributes to mobility policy assessment by proposing four novel indicators and applying them to recent PT fare innovations in Germany. These indicators offer novel insights into individual travel after the introduction of the DT. The analysis is based on the smartphone-based tracking panel

Mobilität.Leben Loder *et al.* (2023) and thus sharpens previous assessments of the DT.

The following sections provide an overview of established and innovative data collection methods and indicators used to describe and assess prominent European fare policy interventions over recent years, focusing on Fare-Free PT (FFPT) and low-cost travel passes. The change in cost-benefit ratio from previous fare regimes to the DT is so immense that this study addresses the DT in the context of FFPT. The remainder of the paper describes the data and methodology before introducing novel indicators for mobility policy assessment. The results of these novel indicators are presented and their relevance is discussed at the end of the paper.

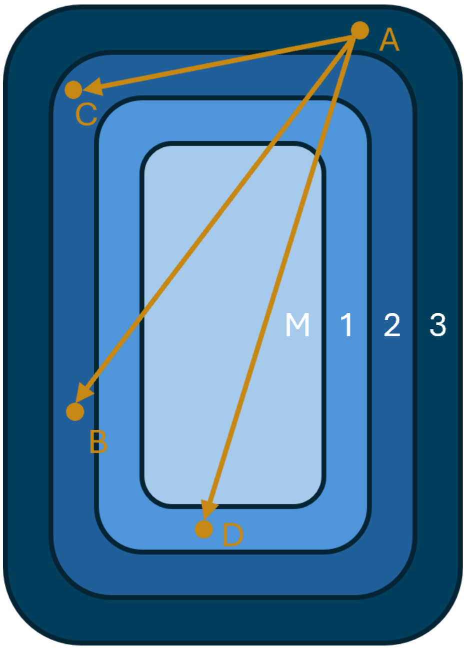
2 Common indicators for fare policy assessment

2.1 Background: Travel Pass Fare Policy in the DACH-Region

PT fare structures within Germany, Austria, and Switzerland (DACH region) are determined by so-called fare associations (Tarifverbünde) and fare zones (Tarifzonen). Within these fare associations, travelers can use all transport modes with a single ticket. The price is based on 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 and micro-mobility. 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 more individual pricing, such as the *homezone*, have been developed Weigele *et al.* (2021).

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 six fare zones. 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. The MVV offers travel passes for a specific period, e.g., day, week, month, or year. They are valid for a particular part or the entire area of the MVV and cost up to several hundred euros per month Münchener Verkehrs- und Tarifverbund (2021b). Nevertheless, they were the cheapest option for regular travelers. After purchasing the ticket up-front, each trip with PT is conducted at zero marginal monetary cost Larsen and Rekdal (2010).

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	
A to D	M, 1, 2, 3	M - 3	

	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€

2.2 FFPT and PT Pricing

Low-cost seasonal tickets and FFPT are two prominent examples of pricing measures in mobility policy. They have been introduced on different levels and with varying objectives for decades. Baum (1973) estimated demand response to free PT and thus was among the first to perform a data-driven, quantitative analysis on the impact of FFPT 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. Today, the distinction between free PT and FFPT Cats *et al.* (2017) highlights that FFPT is not "free" because of non-monetary and external costs. Over the past three decades, technology to collect, process, and analyze data has improved. GPS tracking was used to analyze transport as early as 1996 Wagner (15.09.1997), but 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).

However, passive tracking methods are still prone to errors; tracks may be incomplete, and trips or modes may be wrongly classified Schelewsky *et al.* (2014). The research project MOBIS ETH Zurich (2024); Molloy *et al.* (2022) was among the first to use a smartphone application to collect tracking panel data in a semi-passive travel diary. The Mobilität.Leben study Loder *et al.* (2023) is a further tracking panel based on semi-active travel diaries; it covers a smaller area but twelve months instead of eight weeks.

2.3 Established Indicators

This paper distinguishes between established indicators summarised in Table 1 and innovative indicators summarised in Table 2.

Switzerland has introduced the Generalabonnement (GA) many years ago. 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). 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 DT, in 2023. However, 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 operated a heavily subsidized urban transport Stadtverwaltung Templin (2019). A study from 2003 Storchmann (2003) looked at ridership numbers, (change in) modal split based on trip numbers, and externalities such as emissions, fatalities, and casualties. In another case, the German federal state of Hesse introduced FFPT for all state employees. 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-€ and DT caused many scientific studies on its various effects. Based on traditional active 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 established indicators used for fare policy impact assessment 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
	Molloy (2021); Molloy *et al.* (2022)	– Covid-19 response – 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
9-Euro-Ticket	Andor *et al.* (2023)	– User satisfaction – Trip savings – Emission reductions – Cost-Benefit Analysis	Active surveys
FFPT for State Employees (Hesse)	Busch-Geertsema *et al.* (2021)	– Regularity of mode usage – Commute distance – Perceived accessibility	Online surveys

2.4 Innovative Indicators

Literature 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). Luxembourg 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). Austria introduced the Klimaticket in October 2021, a seasonal ticket for 1095€ per year. Owners of such a Klimaticket can use public local, regional, and long-distance transport systems throughout the country, with a few specific exceptions. Since July 2024, permanent residents who turned 18 in January 2024 or later can order one free Klimaticket, valid for one year, within three years. This is a Partial FFPT measure that will be interesting to analyze in the upcoming months and years. The official accompanying scientific research, the Klimaticketreport Follmer and Treutlein (2023) runs in multiple phases. So far, the Klimaticketreport 2022 has 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. The study is based on semi-passive travel diaries via a smartphone application with 2300 monthly respondents and surveys online and per phone Follmer and Treutlein (2023).

Similar approaches can be found in the context of assessments of the DT 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 travel passes. One such aspect is the equity between different locations Tiznado-Aitken *et al.* (2021); Zhao and Zhang (2019). 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). Calastri *et al.* (2020) integrated data on individual travel choices, which were tracked via a smartphone app, with survey data on energy, residential choice, social networks, and important life events. The study enables research on the cross-cutting effects of multiple phenomena usually addressed in solitary. Schönau (2016) provides an overview of GPS tracking methods and their application before 2016, dating back to 1997. 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).

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, DT	Gaus *et al.* (2023)	– Travel distance per mode – Number of trips per mode – Trip purposes – Purchasing numbers	Passive tracking panel
9-Euro-Ticket	Lu *et al.* (2024)	– Crowding in PT stations	Crowdsensing data (Google Popular Times)
	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
	Krämer (2024)	– Overall travel increase – Modal shift – Travel outside fare associations – Urbanization effect	Mixed data sources

2.5 Recent PT Fare Innovations in Germany

Like its predecessor, the 9-Euro-ticket, the DT 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 DT 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 climate-neutral transport Die Bundesregierung (17.07.2024). Several studies analyzed the DT 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) and draw 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 DT. 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 DT on travel behavior was analyzed in terms of average daily travel distance, change in modal share, and generalized cost of travel Loder (2024). Overall, the studies find an increase in trips and travel distance, decreasing travel costs for owners of the DT, and a shift from car to PT.

3 Method and Data for Novel Indicators

The novel indicators were developed based on gaps identified in the literature 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 in scientific contexts. The Mobilität.Leben study Loder *et al.* (2023) collected semi-active GPS-based travel diaries using a custom-made smartphone app. Participants could download the app and activate their location to track on the smartphone. The app then tracked every trip, including departure and arrival times, speed, and exact route. The app further allocated a transport mode to the trip, which the user could validate or correct. Users could also assign and correct trip purposes or activities to trips and locations. This combination of automated tracking and classification of trips with active oversight by users is called a semi-passive travel diary. The study was conducted from June 2022 through December 2023, covering the end of COVID restrictions, the 9-Euro-ticket, and the introduction of the DT.

The raw data has already been processed and cleaned. For each trip, the data provides the location and time for the start and end, the path as geometry, the distance and duration, the main mode, the purpose, and the duration of the next and previous stay, whether the trip is in Germany and within the MVV, as well as sociodemographic data. The necessary steps and challenges in processing the data before they can be utilized for analysis are outlined in a previous publication Victoria Dahmen *et al.* (2023). The data have been further sorted to fit the purposes of this study. All trips of more than 24 hours or entirely outside Germany were excluded to focus on everyday mobility in Munich. To avoid errors regarding weekly or monthly analysis, all users who tracked less than 2 trips within the MVV region and less than three trips per week were excluded for the specific week. Furthermore, all users for whom no data on the purchase of a DT were excluded. Only trips in September through October in 2022 and 2023 were used. Thus, the same time of year for the period before and after the introduction of the DT were considered, respectively.

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 activity time per fare zone, (b) the monetary travel cost with and without DT, (c) the travel direction per mode and home zone, and (d) the travel time per time of day, weekday, and fare zone.

4.1 Activity Time per Fare Zone

All trips with the purpose of the next stay being "home" or "work" were excluded. These two purposes were considered constant and not dependent on the DT. The activity time per zone represents the average time per person spent in each MVV zone only for activities excluding home and work.

$$A_{z,\ w,\ p,\ t} = \frac{\sum_i^n a_{i,z,w,\ p,\ t}}{n}; w \notin work, home \tag{1}$$

Thereby $A_{z,\ w,\ p,\ t}$ represents the activity time per fare zone z and weekday w for a purpose p which is neither "work" nor "home" and a specific period t before or after the introduction of the DT. $a_{i,z,w,t\ p}$ is the activity time per user i in the respective zone with matching purpose and period. Dividing the activity times by the number of users in this period n enables better comparison between both periods because the number of users in each period has been different. This indicator illustrates how far spatial activity patterns change in response to PT fare innovation. Especially for urban planners, this can be useful information to manage travel demand to or from specific areas. It also indicates the attractiveness and accessibility of regions in relation to monetary transport costs and can be used for equity analyses.

4.2 Monetary Travel Costs With and Without the DT

Calculating the ticket price for PT in fare associations requires geospatial data because the price depends on the traversed geographic area. PT prices are computed by identifying all districts where the respective trip passed. Each district is assigned a fare zone. The ticket price is calculated on each trip's two most distant fare zones traversed.

$$C_{i,m} = \min \left\{ \left(\sum_{\substack{l=1 \\ k=\text{car}}}^{x} c_{m,l} + \sum_{\substack{l=1 \\ k=\text{PT}}}^{y} c_{m,l} \right) ;\ \text{monthlyticket}_z \right\} \tag{2}$$

The cost per month m for a specific user i, $C_{i,\ m}$ was calculated as the sum of all trips $l \in 1 : x$ by car and $l \in 1 : y$ by PT for one month m compared to the cheapest monthly ticket that covered all trips made within that month. The monthly ticket $monthlyticket_z$ and the cost $c_{m,l}$ for single trips are based on the two most distant fare zones z the individual traversed in the respective month.

Beyond the PT price, the price for each trip was calculated for car mode. This was done by multiplying the trip's car distance with the average price per kilometer for the most common car in Germany. According to the latest statistics ADAC e.V. (01.2024), this is 55ct (Euro-cents) per kilometer, based on the VW Golf. The price was calculated for all trips to enable an additional comparison of a counterfactual scenario in which all trips were made with PT or the car, respectively. For the primary comparison, the relevant price was taken based on the main mode of transport, either car or PT. Trips with another main mode of transport were considered cost-free. With this indicator, research better understands the financial impact of PT fare innovations in fare zones, benefiting research, society, and companies alike.

4.3 Travel Direction per Mode and Fare Zone of Residence

The Travel Direction per Mode and Fare Zone of Residence $V_{k,\ inside}$ informs on the travel direction in terms of fare zone of residence h and distinguishes between trips to end zones z that are more central $z < h$, zones that are further outside $z > h$, or trips within the same zone $z = h$.

$$V_{k,\ inside} = \frac{count\left(v_{z,k,h;\ h>z}\right)}{count\left(v_{h,k}\right)} \tag{3}$$

$$V_{k,\ outside} = \frac{count\left(v_{z,k,h;\ h<z}\right)}{count\left(v_{h,k}\right)} \tag{4}$$

$$V_{k,\ within} = \frac{count\left(v_{z,k,h;\ h=z}\right)}{count\left(v_{h,k}\right)} \tag{5}$$

As prices for PT trips tend to be more expensive the further they occur from the city center, an assumption might be that more trips will head outside when PT prices decrease. Another assumption is that more people travel to the city center because it is becoming more attractive. This new indicator can be used to test these hypotheses. The analysis was made on data aggregated by week and as the average per person. Each trip's end zone was compared to the user's fare zone of residence. This approach avoids leveling all inbound and outbound trips when the same trip is done in both directions. All users who live outside the MVV were excluded. The share was then calculated as the ratio of outbound trips, inbound trips, or trips within overall trips by that person in the specific week.

4.4 Travel Time per Time of Day and Fare Zone

The travel time per time of day and MVV zone $D_{j,k,z}$ represents at which time of day people starting in which zone z spend how much time d with travel. For each fare zone, the travel time is summarised over all users i in 48 30-minute intervals $j \in 1:48$ and divided by the number of users x in the sample.

$$D_{j,k,z} = \frac{\sum_{i=1}^{x} d_{i,j,k,z}}{x * q} \tag{6}$$

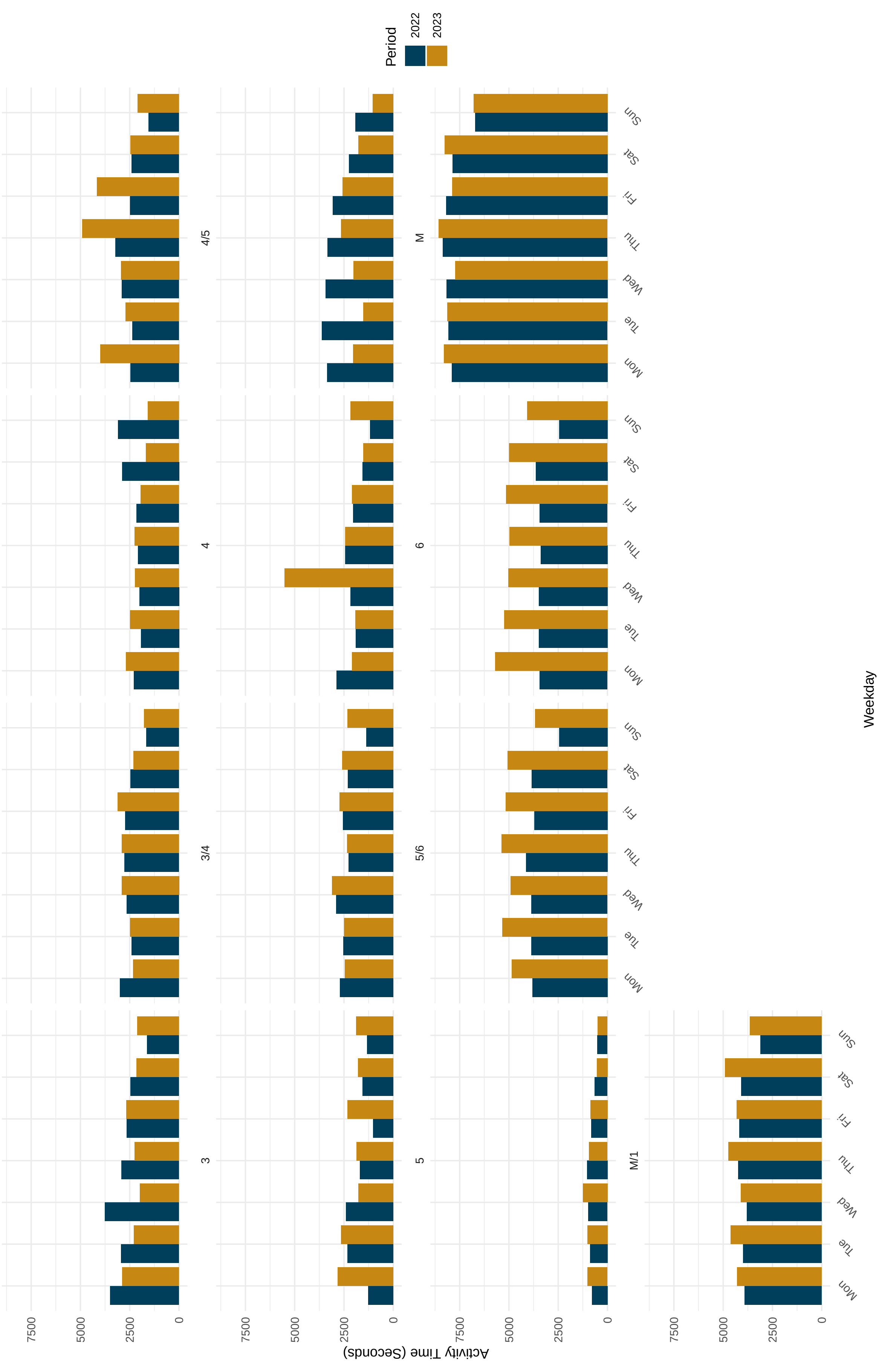
While many studies use travel time as an indicator, the details of spatial and time-of-day distribution are commonly neglected. This indicator can fill that gap and inform planners and researchers of the crucial impacts of PT fare innovations.

5 Results

5.1 Average Activity Time per Weekday and Fare Zone Captures Important Mobility Benefits

The results of the Average Activity Time per Weekday and Fare Zone are summarised in Figure 2 and show slightly higher values in the city center with zones M and M/1 and an even higher increase in the most outside zones 5, 5/6, and 6. In the city center, activity times increased by five to ten minutes per person and 25 to 35 minutes in the most outside fare zones. However, the general trend remained constant: Activity Times per Weekday in the city center are higher, with about four hours than in other areas, with about 1 - 2.5 hours each. The monthly activity time increased overall by almost 20 minutes to well above 3 hours per person after introducing the DT. These numbers are considerably higher than the 1,5h per person in the latest Mobility in Germany survey (MiD) Nobis and Kuhnimhof (2018). While the MiD data represent the average per person in the total population, the data in this study illustrate the average for those who tracked an activity other than home or work in the respective zone on that day. Hence, this new indicator explains how long activities last on average in each fare zone, while the MiD rationalizes how much time every person spent on which activity on average.

Figure 2: Average Activity Times per Zone and Weekday Before and After DT Introduction: More time was spent in the city center and most outside zones after the DT introduction.



5.2 Monthly Travel Costs Decreased After Introduction of the DT

The results of the monetary cost comparison is depicted in Figure 4 Figure 3. The graphs show the average optimal price for all individuals under the current and previous pricing regimes, both for the sample before and after introducing the DT. It compares prior and current optimal spending based on real-world data and between current and imaginary monetary costs if previous fares were applied to current travel patterns. The data show that the average user changed their travel behavior so that their costs for PT would have increased under the last regime pricing but decreased because of the fare intervention, while car travel costs slightly decreased after the DT introduction. The increase in PT travel cost would have been higher for travelers who owned a DT, but they benefited from the reduced price with DT. The average travel expenses, considering the DT, are between 35€ and 39€ and would have been between 65€ and 69€ in the old fare regime. Before the DT was introduced, PT costs ranged from 55€ to 61€. For those owning a DT, the PT travel expenses in the old fare regime would have been 88€ and 94€ but decreased to 41€ to 44€. Car travel costs decreased by up to 40€ per month for this group. Car travel expenses decreased more for those without a DT ownership than those who purchased the DT.

Figure 3: Monthly travel costs in old and new fare regimes: Average travel costs decreased for the entire population compared to 2022 and 2023 with the old fare regime. Own figure.

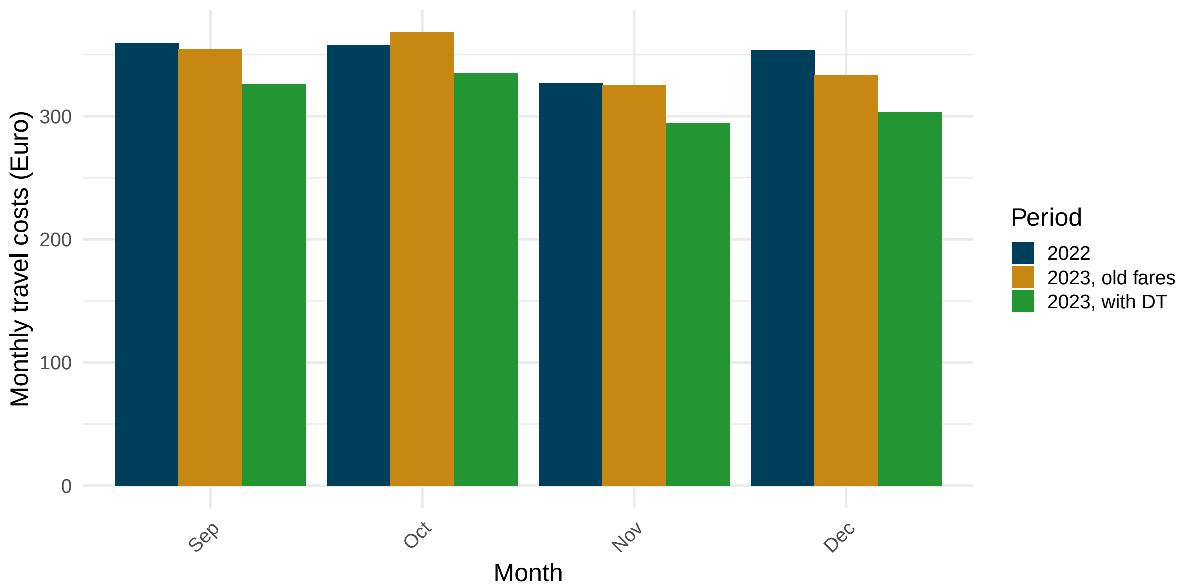
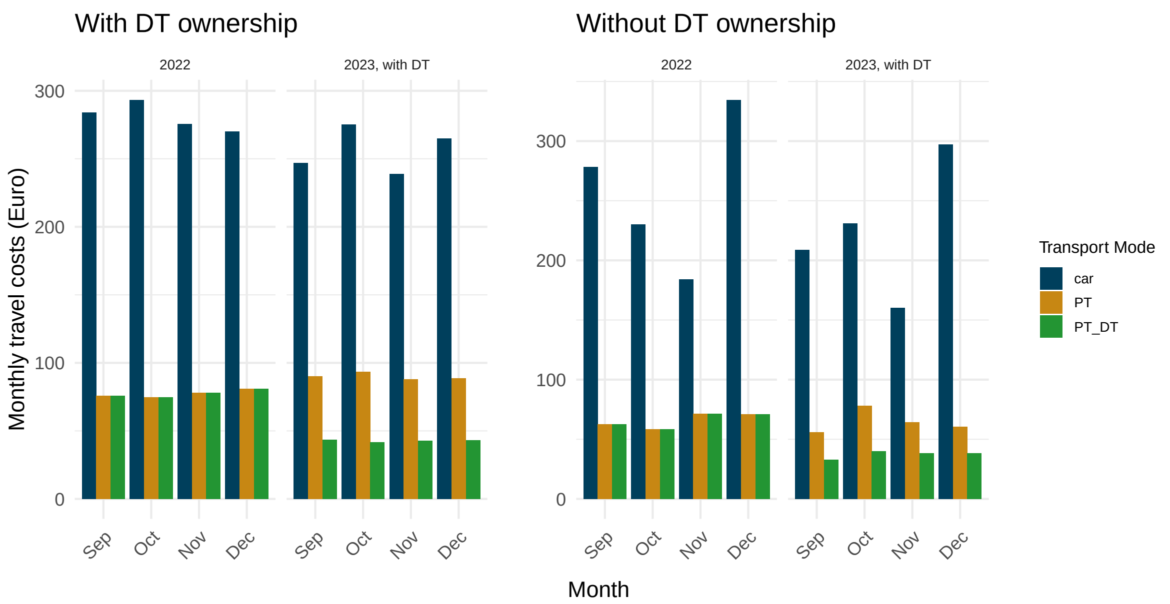


Figure 4: People who own a DT benefit from reduced PT costs, but the group without DT would benefit on average, too. Own figure.

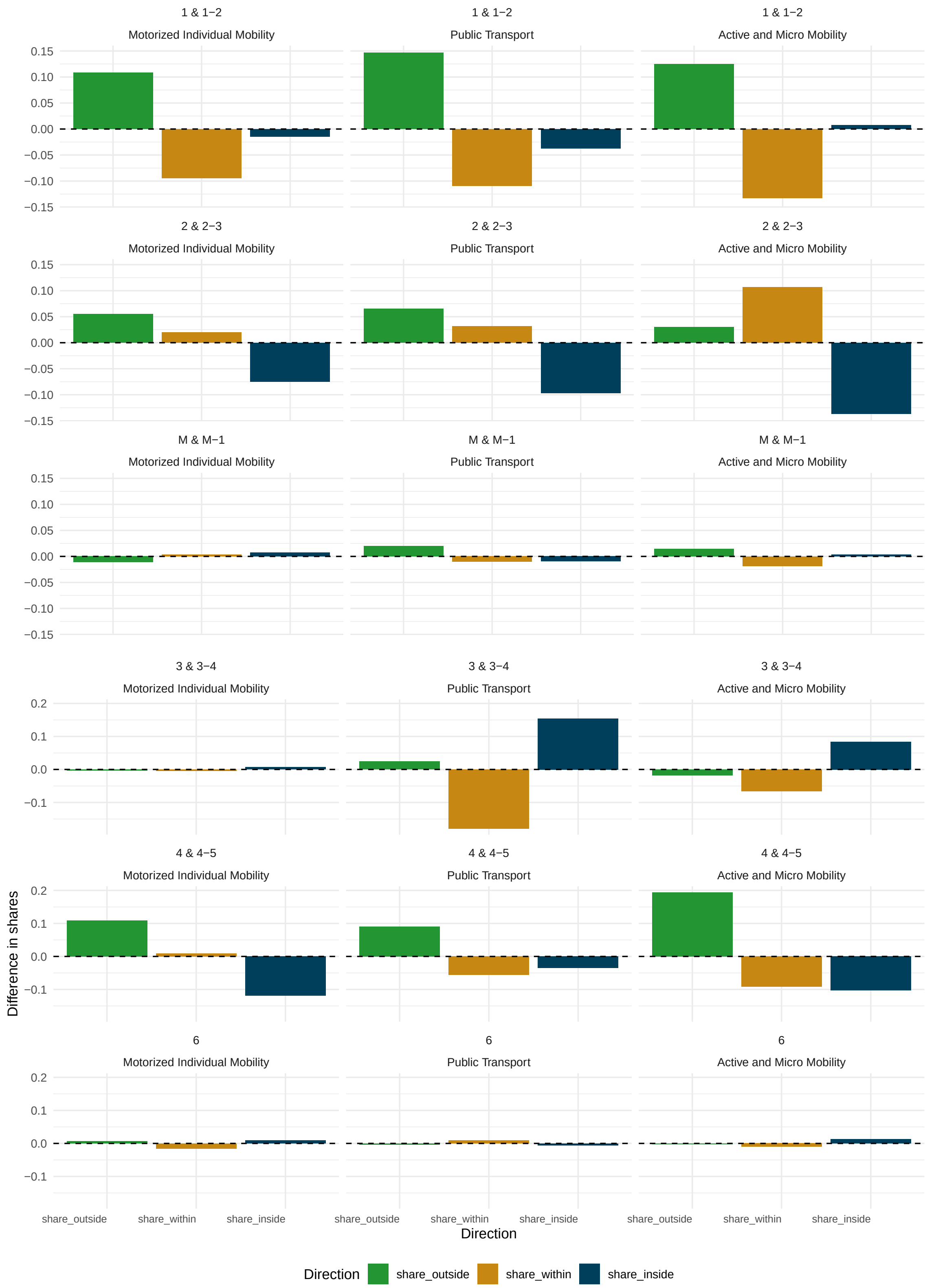


The data reveal an average monthly spending on mobility of about 350€ per person before the introduction of the DT and 340€ to 345€ after the introduction. This is considerably higher than previous findings from 2021 Destatis (2021), which might be caused by high inflation in 2022 as well as high price levels in Munich and a high share of high-income households Loder *et al.* (2024). With previous fares, the monthly spending would have increased to 380€ or even 400€ in October 2023. The average person saves five to ten euros per month because of the DT, including those who did not buy a DT. When comparing the savings to the counterfactual costs, assuming the new travel behavior but old costs, the monthly savings are about 40€ per person.

5.3 Travel Directions Open a New Field of Analysis

Travel directions vary across modes of transport, fare zone of residence, and fare period as illustrated in Figure 5. However, most trips remain in the same fare zone. People living in zones 2, 3, and 4 use T predominantly for trips towards the city center and back. People living in zones 5 and 6 make only a small share of trips to the city center. The share of outbound trips is higher for Motorized individual transport (MIV) and active mobility than PT across all zones except 5 and 6. Across all modes, people in zone 3 made more inbound trips in 2023 than before, while people in zones 1, 2, and 4 made more outbound trips, and the directions of people in zones M, 5, and 6 did not change. The share of trips within one fare zone increased overall, while the share of trips towards the city center or boundary of the MVV decreased. This is also true for PT modes.

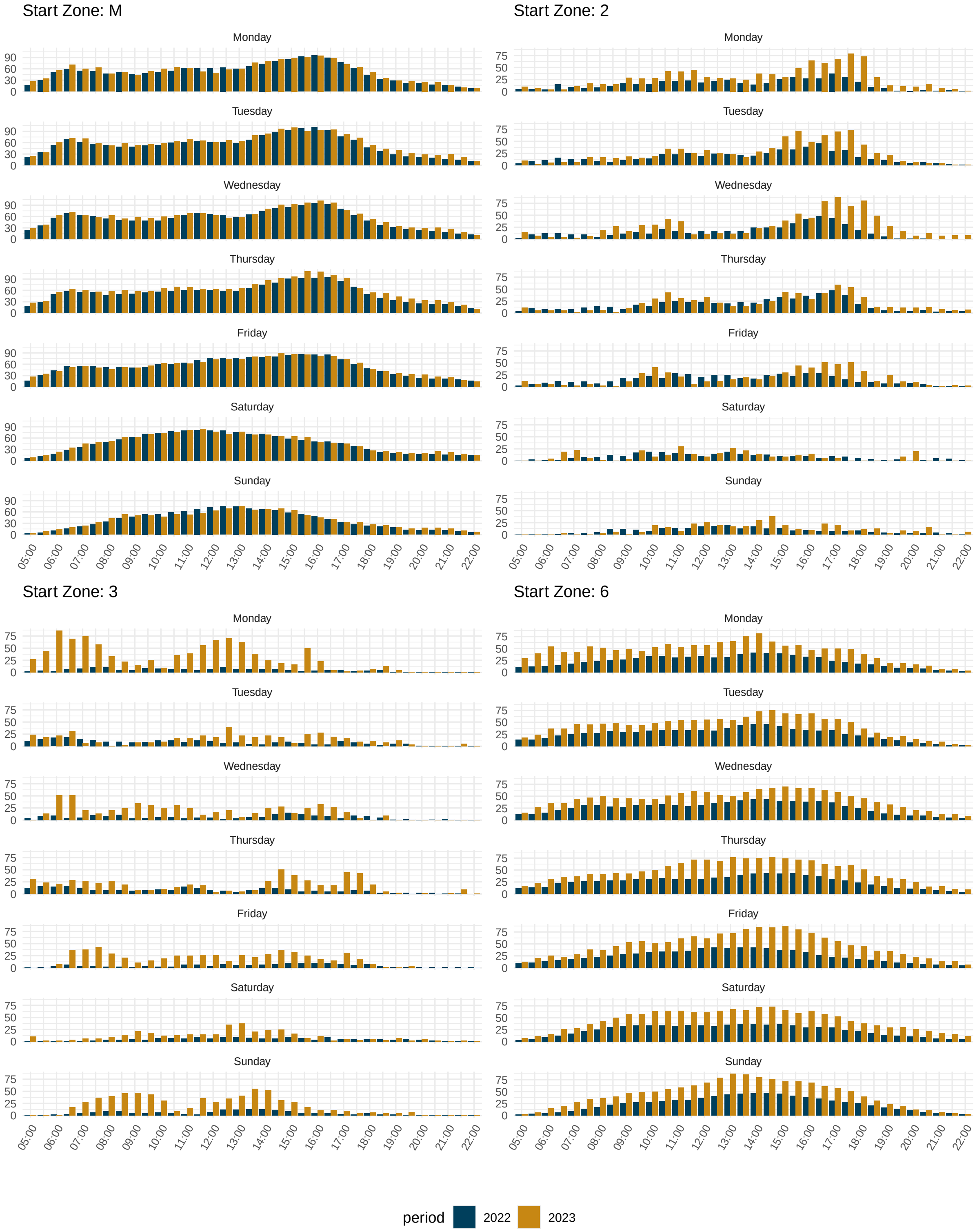
Figure 5: Difference in Travel Directions per Mode and Fare Zone of Residence: Since the Introduction of the DT, More Trips Were Made Within the Same Fare Zone



5.4 Travel Time per Time of Day Change Differently across Fare Zones

The travel time varied across zones, though a distribution across day-time periods and weekdays which was found in other studies Mazloumi *et al.* (2010); Mallig and Vortisch (17.07.2017) was evident in all fare zones. Figure 6 summarises these findings. The travel times were highest in zone M, with 60 to 90 seconds per time interval, and per person, zone 3, with 50 to 75 seconds, is also higher than all other zones, with 20 to 60 seconds, between 6 a.m. and 10 p.m., respectively. After the introduction of the DT, travel times increased overall and across all zones. In most outside zones 3, 4, 5, and 6, the increase was similar across all periods and weekdays. In zone 2, the peak travel times increased, while in zone M, travel times increased between 1:30 p.m. and 4:30 p.m., and in zone M-1, especially on the weekends. Only in zone 1 did travel time per interval decrease, with the only increases on Friday from 4 p.m. to 7 p.m. and 4 a.m. to 6 a.m. during the week.

Figure 6: Travel Times were Highest in the City Center and Increased on Afternoons. Own Figure.



6 Discussion and Conclusion

The paper introduced four novel indicators for mobility policy assessment and produced new insights on the impact of the Deutschlandticket, illuminating the spatial and temporal dimensions of the effects of the Deutschlandticket on travel behavior in the MVV. The novel indicators are (a) the activity time per fare zone, (b) the monetary travel cost in fare associations based on GPS trajectories, (c) the travel direction per mode and zone of residence, and (d) the travel time per time of day, weekday, and fare zone. Despite several studies having rich data on individuals' position in time and space, combining both indicators is largely neglected Lu *et al.* (2024). The presented results underscore the importance of this new perspective, as the impact of public transport fare innovations varies across fare zones, time of day, and time of year. The average travel costs decreased for the entire population. People who owned the Deutschlandticket accumulated the highest savings due to the Deutschlandticket Rozynek *et al.* (2023); Andor *et al.* (2023). People without the Deutschlandticket spent slightly less than before due to decreased car expenses and more on public transport but, on average, would benefit from buying the Deutschlandticket. These results align with the literature 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€ in the respective month with another ticket. More travel cause higher benefits: the average activity time increased after the Deutschlandticket was introduced, suggesting induced demand. The least central fare zones have become more attractive destinations for activities outside home or work, having the highest increase in activity times, though the city center remains most frequented. 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). While the monetary cost decreased after the public transport fare innovation and activity time increased, travelers spent more time on travel, reflecting previous findings Verband Deutscher Verkehrsunternehmen e. V. *et al.* (16.12.2022); O2 Telefónica (2023). The change in travel time is not constant over fare zones and weekdays but depends on the zone in which each trip started. This is an essential insight for planners as it informs about local and time-specific demand changes after public transport fare innovations; according to the data, the city center sees increasing demand on the weekend, while the most distant fare zones see an increasing demand over the entire day and each day of the week. This motivates further research on whether the rise in mobility or capacity overload causes the variation in travel time increase. The share of trip directions hardly changed after the Deutschlandticket was introduced. With increasing trip numbers Loder *et al.* (2024); Verband Deutscher Verkehrsunternehmen e. V. *et al.* (16.12.2022); O2 Telefónica (2023), the total number of trips across fare zones also increased with the Deutschlandticket. The high share of trips within the fare zone suggests a high impact factor of fare zones, but the small effect of abolishing these zones contradicts this interpretation. As expected, the highest share of inbound public transport trips occurred in fare zones near the city center, and the share of outbound trips increased for the most central zones. The public transport fare innovation had little effect on the least central zones. Further studies are necessary to understand the causalities of trip directions and to examine how far the effect differs between owners of the Deutschlandticket and those without a Deutschlandticket.

The study acknowledges limitations due to the novelty of the indicators, which were not considered during data collection. This resulted in incomplete data. Car travel expenses were estimated using average costs per km, which may not reflect actual monthly expenses. Public transport cost data do not specify if the optimal ticket was purchased, but the approach estimates optimal costs based on actual trips. Some cheaper ticket combinations were not considered for simplicity. Activity purposes were also incompletely recorded, limiting the validity of activity time results. Future studies should apply these indicators to more representative data for better validity.

In closing, the novel indicators extend the methodology of mobility policy assessment by combining spatial and temporal perspectives. They enhance equity analysis, increase quality of important transport parameters and extend the scope of fare innovation assessment. Accessibility and equity are part of the UN SDGs and essential to fare policy assessment United Nations Department of Economic and Social Affairs (2024); Oviedo *et al.* (2022); Hackl (2018); Bertolini (2020). Accessibility studies so far focus on affordability or days without travel Cats *et al.* (2017). The novel indicators enrich spatial considerations of equity and accessibility; impacts of public transport fare innovations can now be compared across fare zones or areas of residence Zhao and Zhang (2019); Tiznado-Aitken *et al.* (2021). Differentiating the activity times between fare zones allows conclusions on changing attractiveness of an area in response to public transport fare innovation, indicating spatial equity differences. The travel time per fare zone and time of day reveals if people from certain areas spent more or less time on transport than others and at when people in this zone have to travel. The cost indicator illuminates who benefits how much from the Deutschlandticket Andor *et al.* (2023). Societal savings and spending could be compared, similar to the cost-effectiveness analysis in the context of emission savings Andor *et al.* (2023). In the context of an announced price increase for the Deutschlandticket in 2025 MDR (2024-07-09), 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). Activity times capture another essential dimension of mobility benefits Mokhtarian and Salomon (2001) and make it accessible for mobility policy assessment. Including more precise measures of the individual benefits people gain from a fare innovation into equity analysis will provide new insights and higher assessment quality. Beyond accessibility and equity, the indicators can be used for better estimations of transport parameters. This paper is the first to calculate prices in a fare association based on smartphone-based tracking data in a multi-month, real-world scenario. The results can be used to derive more precise estimates for travel demand and the value of travel time. The travel time per time of day and fare zone allows detailed insights into the spatial distribution of effects of on individual travel from public transport fare innovation. It demonstrates whether travelers from one zone travel more or less than those from another and when they do so. This can inform traffic planners to estimate local demand at specific times and locations and thus to identify peak hours. Combining money and time cost, price elasticities can be determined from precise real-world data on changes after a fare innovation with better quality. Potentially, travel directions proof to be a relevant factor for price elasticities or the value of travel time. Finally, the indicators allow a more detailed measurement of the impact of fare policy decisions. Travel costs and savings can now be calculated based on spatial trajectories, even in complex fare regimes like fare associations Münchener Verkehrs- und Tarifverbund (2021b). Activity times at different locations, the primary reason for travel Mokhtarian and Salomon (2001), can be addressed in assessments. Travel times can be differentiated across time of day and location to develop an integrated view on impacts of fare innovation. he 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 shape of these *homezones* provide valuable insights. In conclusion, the four novel indicators contribute to the methodology for public transport fare innovation assessment; even complex fare structures like fare associations can be precisely analyzed. The indicators provide relevant insights for researchers, planners, and policymakers in the context of budget constraints and increasing public demand for accessibility, sustainability, and equity, as expressed in the United Nations SDGs United Nations Department of Economic and Social Affairs (2024).

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8 Authors Contribution

The authors confirm their contribution to the paper as follows: Martin Schlett: Conceptualization, Methodology, Formal analysis, Writing, Visualization. Allister Loder: Data collection, Supervision. All authors reviewed the results and approved the final manuscript.

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