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The Mobilität.Leben Study: A 20-Month Mobility-Tracking Panel

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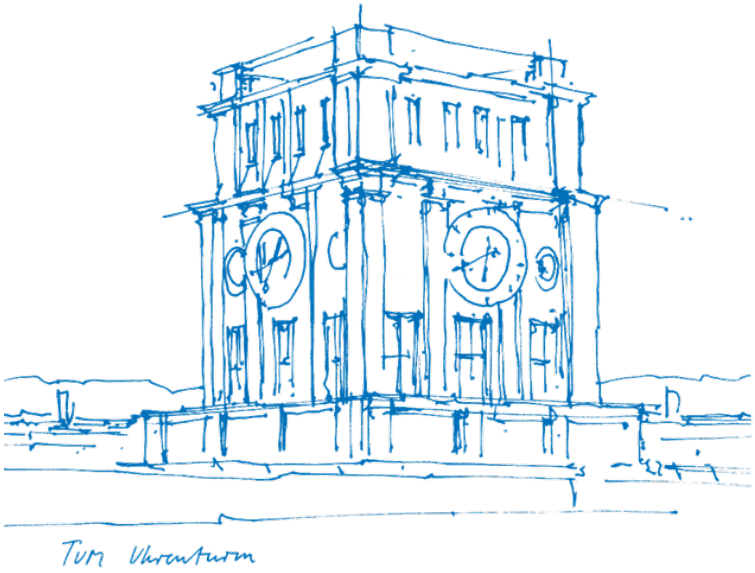

The Mobilität.Leben Study: A 20-Month Mobility-Tracking Panel

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Abstract

The “Mobilität.Leben” study is a twenty-month panel study with a six-wave survey and semi-passive travel diaries with waypoint tracking using a smartphone app that was initiated to observe natural travel behavior interventions in Germany in the years 2022 and 2023. In response to the 2022 cost-of-living crisis, the German government introduced two temporary policy measures to reduce travel costs using a fuel excise tax cut and almost fare-free public transport with the so-called “9-Euro-Ticket”. The latter policy has been made permanent in 2023 with the “Deutschlandticket”, which is priced at 49 Euro per month. This paper presents the study design of“Mobilität.Leben”, its survey method, the overall sample and travel characteristics, as well as shares the experience of conducting such a large-scale study. The “Mobilität.Leben” study includes 2,624 individuals who were either self-recruited primarily in the Munich metropolitan area or externally recruited from the entire nation through a professional agency. In total, 1,140 individuals used the smartphone app and reported travel behavior with the smartphone app; 218 individuals completed the survey and reported travel behavior from before the introduction of the “9-Euro-Ticket” towards long after the introduction of the “Deutschlandticket”. We can conclude that conducting year-long panel studies is possible, providing rich information on the heterogeneity in travel behavior between and within travelers. However, one should be aware of the required resources to ensure high data quality.

Suggested Citation

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1 Introduction

In response to the 2022 cost-of-living crisis in Europe, the German government introduced a three-month fuel excise tax cut and a public transport season ticket for 9 Euro per month, valid on all local and regional services, the so-called "9-Euro-Ticket". The latter can be considered almost fare-free public transport, considering that 9 Euro is less than the minimum wage in Germany at that time. The intervention months were June, July, and August, i.e., a period characterized by summer holidays. Given the critical role of travel costs in mode choice (Hensher and Stopher, 1979), this natural experiment was expected to lead to a modal shift to public transport because the season ticket price cut was so substantial. In addition, many expected that the almost fare-free aspect of the "9-Euro-Ticket" leads to high levels of induced demand. The success of the "9-Euro-Ticket" prompted an immediate discussion and public as well as political demand for introducing a successor ticket to the "9-Euro-Ticket" as soon as possible. This ticket, the so-called "Deutschlandticket", was finally introduced in May 2023 at 49 Euro per month.

This behavioral intervention, which could be one of the largest public transport pricing travel behavior experiments, has been studied by many: all of them reported a substantial increase in public transport usage during the validity period of the "9-Euro-Ticket" and a return to almost pre-ticket levels after the "9-Euro-Ticket" validity period (Loder *et al.*, 2024; Verband Deutscher Verkehrsunternehmen (VDV) *et al.*, 2022; Gaus *et al.*, 2023; Loder *et al.*, 2023; Krämer *et al.*, 2022; Dietl and Reinhold, 2022). The official and main study was conducted by Association of German Transport Companies, which surveyed more than 200,000 people in Germany (Verband Deutscher Verkehrsunternehmen (VDV) *et al.*, 2022): around 20% of all "9-Euro-Ticket" customers were new customers to public transport. Out of all public transport trips in the months of June, July, and August 2022, 17% of trips have been shifted from other transport modes, and 10% of trips have been shifted from the car to public transport, in rural areas, even 13 to 16%. 16% of all trips correspond to induced demand. In addition, trip distances increased by 38% during the "9-Euro-Ticket" period. Another survey showed that 11% of all trips conducted during the "9-Euro-Ticket" period shifted from other modes of transport, while 6% of all trips were induced (Krämer *et al.*, 2022). Using surveys and GPS tracking, another study concluded that the "9-Euro-Ticket" did not lead to a change in daily mobility but instead increased leisure travel at the beginning and the end of the ticket's validity period, leaving monetary savings as the main effect of the "9-Euro-Ticket" (Gaus *et al.*, 2023). Generally, the summer months of June, July, and August usually see less ridership due to the summer holidays, but in 2022 this trend was reversed (Dietl and Reinhold, 2022). For the "Deutschlandticket", first results for the Hamburg metropolitan area suggest that season-ticket ownership increased by 22% and ridership increased from 89.3% to 95.4% of the pre-pandemic levels from April

to May 2023 (Dey, 2023). From a mobility policy perspective on social participation, using a causal inference approach, a study showed that the "9-Euro-Ticket" was more effective than the "Deutschlandticket" at reducing the probability of never using public transportation and increasing participation in leisure activities (Waldorf *et al.*, 2024).

We set up the "Mobilität.Leben" study to observe both fare policy innovations using questionnaires and semi-passive travel diaries with waypoint tracking. This paper presents the methodological approach of "Mobilität.Leben"sing questionnaires and smartphone-based semi-passive travel diaries, or GPS tracking. We introduce the study design, the recruiting process, and the study participation in the questionnaires and the tracking. We further share our experiences in recruiting, user attrition, and data completeness to make recommendations for future studies of similar panel size and duration. Our experiences and methodological contributions regarding the processing and enriching of the GPS-based semi-passive travel diaries are provided in (Dahmen *et al.*, 2024), with an application to mode choice modeling in (Dahmen *et al.*, 0).

2 Smartphone-based travel surveys

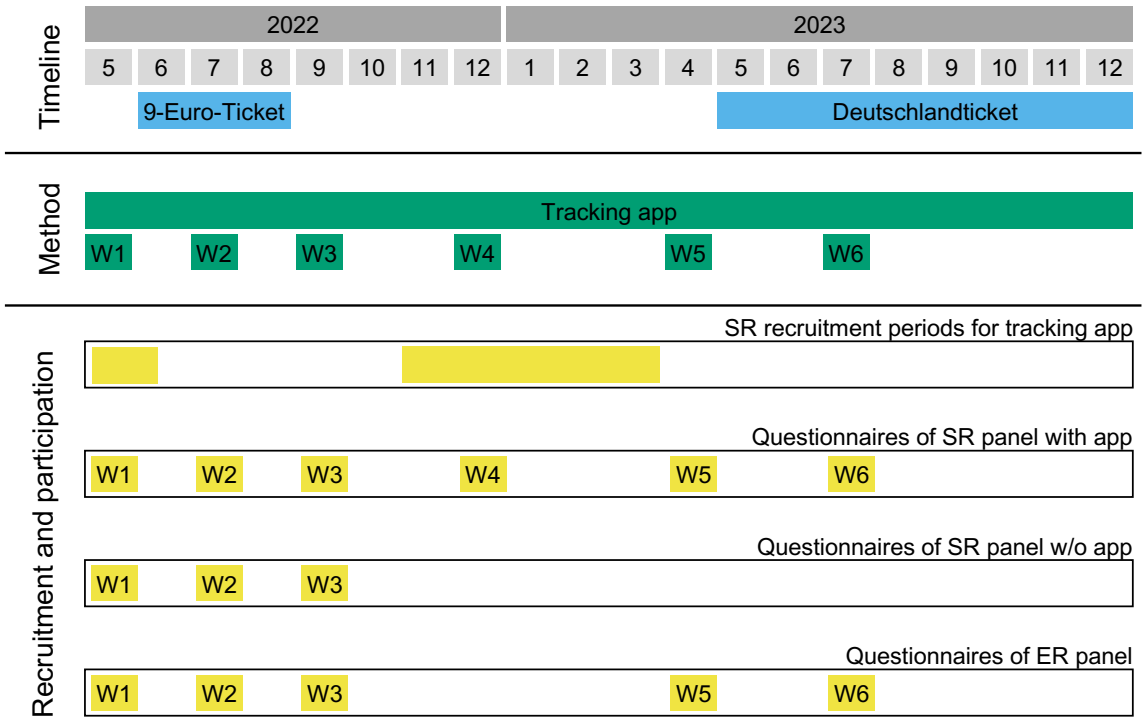
The standard method for travel surveys has been for many years a paper-and-pencil or computer-assisted survey on the web or phone with travel diary (Stopher and Greaves, 2007). This method has also been used by most studies observing the "9-Euro-Ticket" or "Deutschlandticket", either in a cross-sectional (Verband Deutscher Verkehrsunternehmen (VDV) *et al.*, 2022; Krämer *et al.*, 2022; Dietl and Reinhold, 2022) or panel design approach (Francke, 2022; Schlueter, 2022), but is also standard for nation-wide household travel surveys (Eisenmann *et al.*, 2018; Weis *et al.*, 2021; Swiss Federal Statistical Office and Swiss Federal Office for Spatial Development, 2017). Nevertheless, already in 2007 did Stopher and Greaves recognize the opportunities of using GPS devices for the data collection for travel diaries, where GPS data should be combined with the relevant demographic data and specialzed stated choice surveys (Stopher and Greaves, 2007).

The complexity of the fare-policy innovation with the "9-Euro-Ticket" and the "Deutschlandticket", where not only prices change, but also the access provided by these travel passes changes substantially, a standard method with a paper-and-pencil or computer-assisted survey might not be able to cover the full variance of changes in travel behavior. For example, one can expect that self-assessments of how individuals travel across transit district zones and district

borders can only be answered reliably by individuals with some knowledge of the fare system, not everyone. Here, using GPS tracking can be considered an appropriate supplement or substitute to questionnaires to measure travel behavior and its changes over a long time period (Shen and Stopher, 2014). Such tracking-based survey approaches generally work in creating travel diaries (Giaimo *et al.*, 2010), and it is beneficial in correcting under- or false reporting in traditional approaches (Wolf *et al.*, 2001; Stopher *et al.*, 2007; Bricka *et al.*, 2009). GPS tracking can be done using either GPS loggers, where users can edit or validate entries later on a web browser, or smartphone-based, where users can edit and validate entries directly in the app to create semi-passive travel diaries. Comparative analyses of these approaches suggest that key differences are in the organization of the study (sending out and collecting GPS loggers vs. installing an app) and selection bias, as not everyone has a smartphone or a good command, while both data sources can extract "meaningful diaries" (Montini *et al.*, 2015; Stopher *et al.*, 2018). Generally, such rich data improves the understanding and modeling of the complex dynamics of individual activity patterns, e.g., as shown in (Cirillo and Axhausen, 2010; Islam and Habib, 2012; Bhat *et al.*, 2016).

Such survey design has already been successfully tested and implemented. In practice, some countries have already piloted the use of GPS-based travel diaries from the early 2010s onwards. For example, Singapore piloted in its 2012 and 2013 smartphone-based travel surveys in their national household travel survey where 793 participants collected at least 14 days of travel data through the smartphone app (Zhao *et al.*, 2015); New Zealand tracked 73 participants over on average 5 to 6 days in 2014 (Safi *et al.*, 2015); The Netherlands conducted a pilot for the Dutch Mobility Panel with 615 participants over four weeks in 2015 after discussing its use already in 2012 (Thomas *et al.*, 2018; Hoogendoorn-Lanser *et al.*, 2015). For the 2018 household travel survey in the metropolitan area in Minnesota, a comparison was made between the standard approach and a smartphone-based all-in-one approach, where the researchers report that the latter has overall lower recruitment and completion rates, but it promisingly increases the representation of younger and lower-income populations (Lynch *et al.*, 2019). Also for research, this method has been used to collect data (Berger and Platzer, 2015; Molloy *et al.*, 2022; Axhausen *et al.*, 2021; Heinonen *et al.*, 2023; Winkler *et al.*, 2022), but this data collection method is nevertheless still part of research and is improved. Here, two recent contributions to the literature share their experiences on study design and recruiting: Toronto, with 544 completed surveys with up to 60 recorded days (Faghih Imani *et al.*, 2020) as well as from Sydney, with 123 participants completed the survey (Siripanich *et al.*, 2024). This paper aims to contribute in a similar fashion to the literature as the latter two publications by sharing experiences in the design, recruitment, participation, and implementation of the smartphone-based study.

Figure 1: “Mobilität.Leben” study design

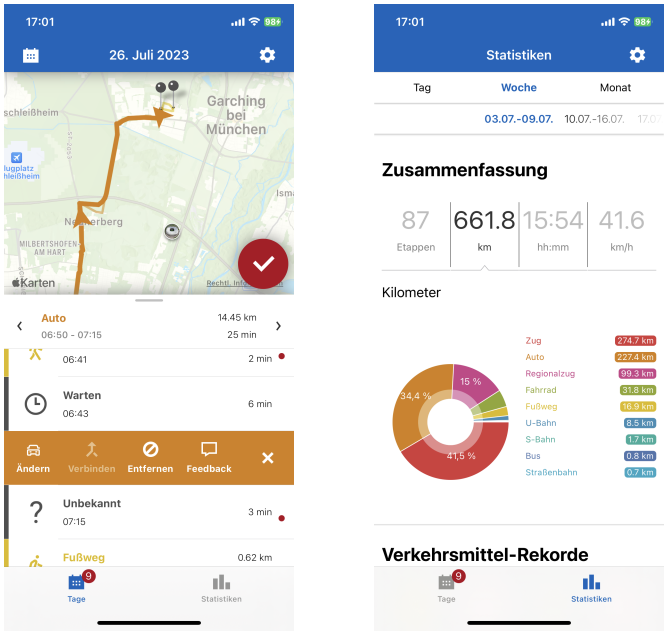


3 Study design of “Mobilität.Leben”

The overall study design of “Mobilität.Leben” is shown in the upper part of Figure 1. It covers 20 months with the time ranging from the time before the introduction of the “9-Euro-Ticket” and the fuel tax cut until the first months of the “Deutschlandticket”. The validity periods of both tickets are shown in blue in the upper part of Figure 1. The study method is shown below in green in Figure 1: The study comprises two parts: in total, six questionnaires as well as the semi-passive travel diaries with waypoint tracking. The fourth wave, “W4”, was a special questionnaire: given the high cost of energy, it focused on energy consumption and energy conservation measures as well as aimed at motivating participants to keep on using the smartphone-based travel diary, because at that point in time the starting date of the “Deutschlandticket” and, thus, the total study duration was unknown. The six questionnaires were online questionnaires, each of around ten to fifteen minutes in length. They contained socio-demographic questions, questions on mobility tool ownership, and their transport- and energy-related attitudes. Every questionnaire also asked respondents about their travel behavior and their travel behavior changes as a consequence of the “9-Euro-Ticket” and “Deutschlandticket”. Given the cost-of-living crisis, we also asked respondents in every questionnaire about the impact of this crisis on their households. Once recruited, participants received invitations and reminders for the

Figure 2: Screenshots of the smartphone track app with semi-passive travel diary.

a) Single travel diary entry b) Weekly statistics



surveys and app via email. This email account also served as the contact point for questions and reporting issues with the smartphone app.

Figure 2 shows screenshots of the smartphone app. It displays the travel diary on a map and allows one to edit the entry, comment on entries, and validate entries (Figure 2a). The user sees the following attributes: start- and end times, travel distance, travel distance, and detector or edited mode of transport. The app also features a screen where users can see their personal travel statistics (Figure 2b).

The short planning duration from the announcement of the “9-Euro-Ticket” on 24 March 2022, passing parliament on 20 May 2022, and its start on 1 June 2022 had implications on the study design of “Mobilität.Leben”. The late passing of parliament meant that we had to wait for the public announcement of our study, which in turn reduced the time available to record travel behavior before the introduction of the “9-Euro-Ticket”. Our study was publicly announced on 23 May 2022, and the first tracking measurements were recorded on 25 May 2022. Further, the general ad-hoc design of the first period of “Mobilität.Leben” as well as the uncertainty of the actual introduction of the “Deutschlandticket”, made a perfect a priori design of the study, its testing, and its communication to study participants impossible. For example, the starting date of the “Deutschlandticket” was initially announced to be 1 January 2023, but it was postponed several times until the ticket finally started on 1 May 2023.

4 Recruiting

The recruiting for "Mobilität.Leben" relied on the self-recruiting (SR) of a convenience sample in the Munich metropolitan region using a media campaign as well as on an externally recruited (ER) representative nationwide sample. The self recruitment required participants to complete a registration form and give their consent for the study participation, while the external recruitment was made by a professional agency. The key reason for the two-part approach: the limited time to set up the study implied that we did not expect that the self-recruiting would lead to a representative sample, neither at the Munich metropolitan region level nor at the nationwide level. Thus, to guarantee at least representativeness in the survey responses, we tasked a professional agency with external recruitment. For technical and organizational reasons, the ER panel could not use the smartphone app overall. In addition, some recruited SR panel members could not install or activate the app on their smartphones and thus also participated only in the survey. This leads to three different panels within the "Mobilität.Leben" study:

- Self-recruited (SR) panel with the travel diary app. Considering the two recruiting periods in Figure 1, this panel has three subgroups: "all" when collected data for the "9-Euro-Ticket" and "Deutschlandticket" "net" when collected data only for the "9-Euro-Ticket" and "dt" when collected data only for the "Deutschlandticket".
- Self-recruited (SR) panel without the travel diary app
- Externally-recruited (ER) panel without the travel diary app

For the SR panel, we recruited two times. Once before the start of the "9-Euro-Ticket" and once before the start of the "Deutschlandticket". Figure 1 shows the time period when participants could register for the study. The lower part of Figure 1 shows in yellow the survey participation of the three panels. Only the SR panel with the travel diary app participated in all six questionnaires. The SR panel without the travel diary app only participated in the first three questionnaires, i.e., about the "9-Euro-Ticket", but was subsequently removed from the study as they did not participate in the smartphone-based travel diary. Participants of the ER panel were not invited to the fourth wave as the objective of this wave was, as aforementioned, to ask questions about energy use as well as to motivate participants to continue the data collection with the smartphone app.

Regarding the compensation for the study, all three panels received different amounts: The SR-panel with the travel diary app received a voucher of 30 Euro when completing survey waves one to three as well as collected travel diaries until September 2022, i.e., for the "9-Euro-Ticket", when completing survey waves five and six as well as recording travel diaries before and after the introduction of the "Deutschlandticket", they received a voucher of 20

Euros. Thus, participants who completed all survey waves as well as collected travel diary data from the introduction of the "9-Euro-Ticket" until after the introduction of the "Deutschlandticket" received in total 50 Euro. Participants in the SR panel without a smartphone app received no compensation for the study. Participants from the ER panel received compensation of about 1 to 2 Euro for each completed questionnaire, which was directly paid through the external agency.

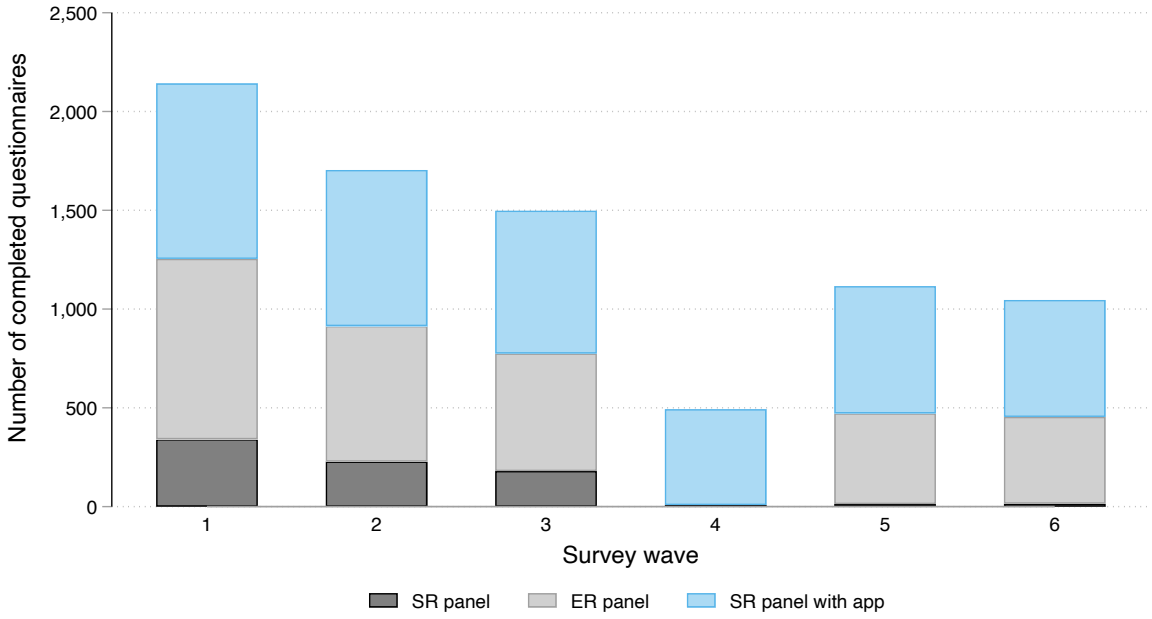
Note that an undisclosed number of study participants requested that all their data be deleted. Consequently, these respondents are not included here. This explains why some participation numbers reported here differ from previously published reports. Additionally, as this paper aims to contribute with methodological experiences regarding tracking and survey panel studies, we do not exclude any observations, although some observations are clearly outliers.

5 Study participation

The aforementioned recruitment strategy resulted in the following sample: 2,624 participants registered for the study with 1,140 in the SR panel with the smartphone app (912 recruited in the first period, 228 in the second period), 566 in the SR panel without the smartphone app, and 918 participants in the ER panel. As the smartphone app had to be manually installed and activated on the participant's smartphone, not every registered participant eventually managed to get the app running. Here, we observed that in the first recruitment period, 16.7% of participants never activated the smartphone app, while in the second period, 25% never activated the smartphone app. It is unknown to us whether the higher activation rate in the first period is a result of the larger study compensation or due to the higher interest in research on the "9-Euro-Ticket". However, evidence from another study suggests that a higher compensation slightly improves study participation (Winkler *et al.*, 2022).

The survey participation of each panel is shown in Figure 3. It shows, ignoring the fourth wave, a steady decline in questionnaire completion rates over time for all three panels, even though for the fifth and sixth waves, new study participants were recruited for the SR panel with a smartphone app, and despite receiving a study compensation. Note that the fourth wave was not sent to participants recruited through the professional agency as the objective of this wave was to understand energy conservation measures taken by households, to motivate participants to continue using the smartphone app as the start date of the "Deutschlandticket" was unknown.

Figure 3: Completion of the six survey waves by panel.

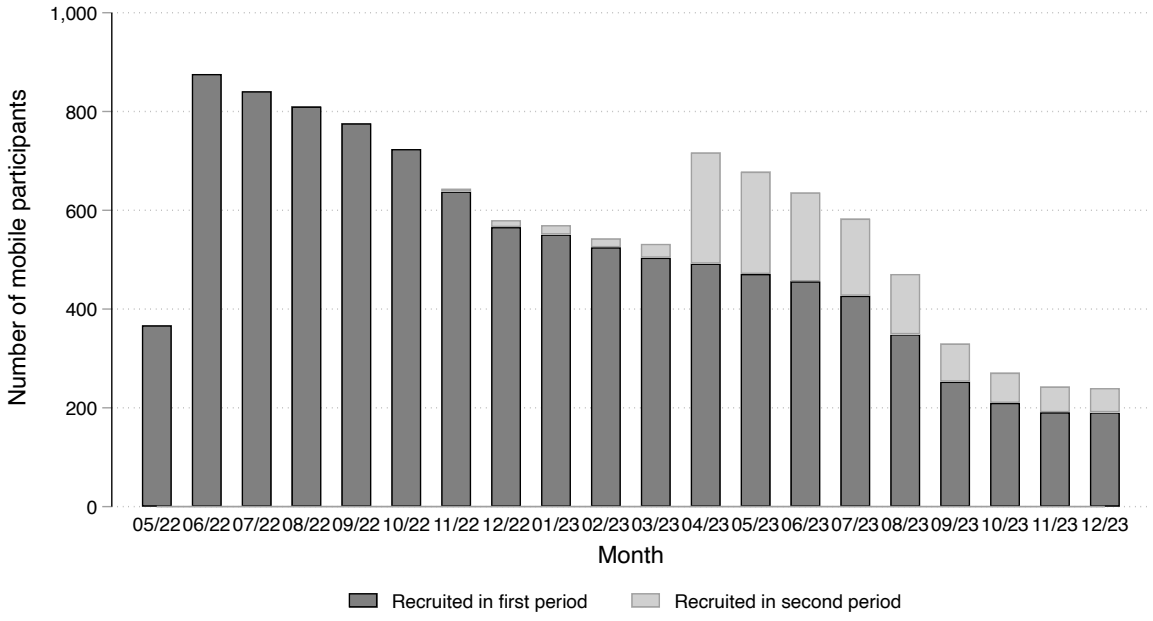


5.1 Use of the smartphone travel diary

The smartphone app for the semi-passive travel diary generation has been successfully activated and used by 1,140 participants; of these, 912 were from the first recruitment period and 228 were from the second recruitment period. Figure 4 shows the number of mobile participants per month from May 2022 until December 2023, where a participant is considered mobile when having at least one day in her travel diary. Participation peaked in June 2022 with 876 app users, i.e., at the start of the "9-Euro-Ticket"; in addition, the short-term start of the "9-Euro-Ticket" and the ticket is exemplified in lower participation numbers in May 2023 (app tracking started on May 25th). A second peak is observed in April 2023 with 717 app users, i.e., right before the start of the "Deutschlandticket". Here, 492 users were from the first recruiting period and 225 from the second recruiting period.

As known from other studies (Molloy *et al.*, 2022), participation dropped steadily once recruiting had been completed. From Figure 4, we can infer the attrition rate, i.e., the share of participants dropping out of the sample. As those participants recruited in the first period received compensation (30 Euro for tracking during the "9-Euro-Ticket" and 20 Euro for tracking during the "Deutschlandticket"), while those in the second period did not. The differences in the attrition rate are informative: the group of participants receiving compensation had an attrition rate of around 3.6%, while the group of receiving no compensation had an attrition rate of 9.4%. This

Figure 4: Time series of the number of mobile app users per study week.

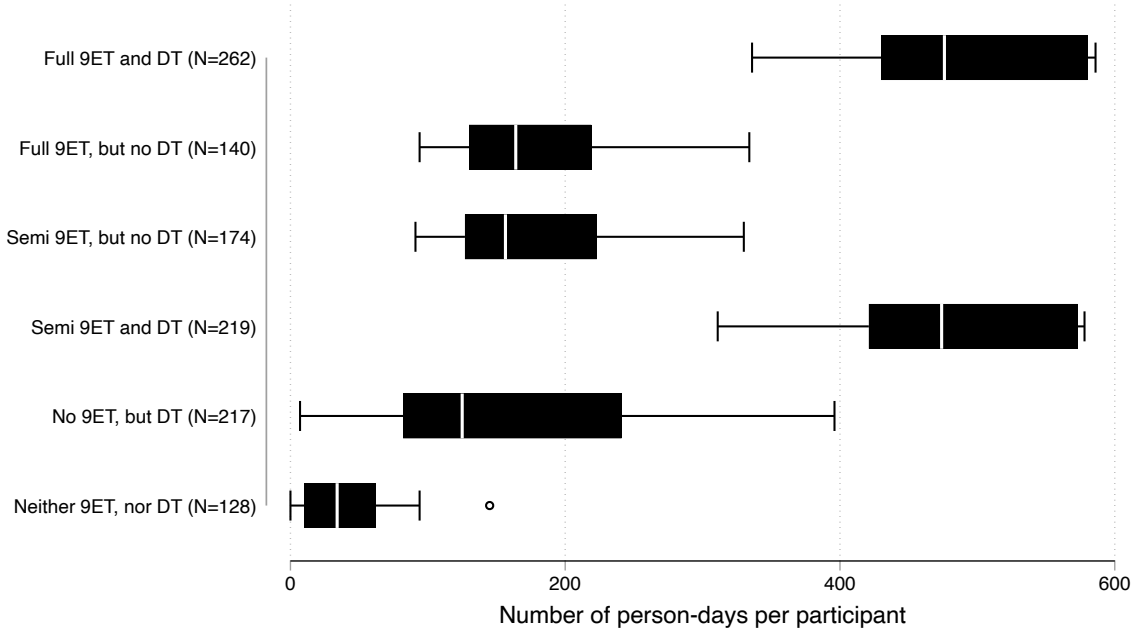


difference can be attributed to the economic incentive that also has been reported for other studies (Winkler *et al.*, 2022).

User participation in such tracking studies is commonly measured in "person-days," which counts the number of fully tracked days of a participant. Figure 5 shows this measure for different groups within the SR panel with a smartphone app. We further divide this panel into groups to distinguish by when a participant started and ended collecting data:

- Full 9ET and DT: Participants from the first recruiting period who collected travel diary entries throughout the entire "Mobilität.Leben" study.
- Full 9ET, but no DT: Participants from the first recruiting period who collected travel diary entries from May 2022 onwards, but dropped out before the start of the "Deutschlandticket"on May 1st, 2023.
- Semi 9ET, but no DT: Participants from the first recruiting period who collected travel diary entries from June 2022 onwards, but dropped out before the start of the "Deutschlandticket"on May 1st, 2023. This group is called "semi" as pre-intervention data for the "9-Euro-Ticket" is not available from them.
- Semi 9ET and DT: Participants from the first recruiting period who collected travel diary entries from June 2022 onwards until the end of the "Mobilität.Leben" study, which includes the introduction of the "Deutschlandticket". This group is called "semi" as

Figure 5: Number of person-days per participant and group within the SR panel with smartphone app.



pre-intervention data for the "9-Euro-Ticket" is not available from them.

- No 9ET, but DT: Participants from the second recruiting period who collected at least one travel diary entry after the introduction of the "Deutschlandticket" on May 1st, 2023.
- Neither 9ET, nor DT: Participants from the second recruiting period, i.e., after the end of the "9-Euro-Ticket", who did not collect any entry after introducing the "Deutschlandticket" on May 1st, 2023.

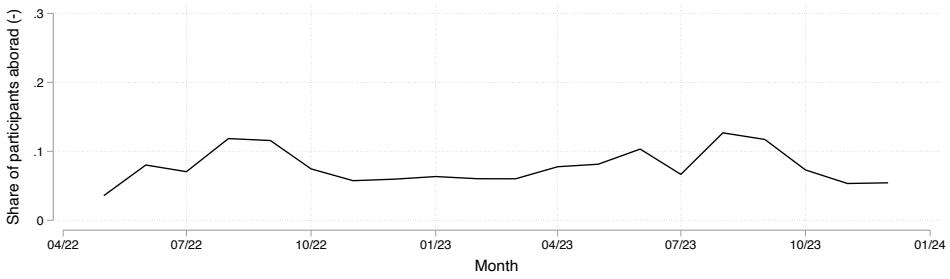
The panel attrition seen in Figure 4 is also visible in the distribution of person-days in Figure 5. Each group shows substantial variation, while also suggesting a pattern of how many person days can be robustly expected for a given time period per person. Overall, it can be concluded that in such a study design, the frequently discussed 14-day threshold for travel diary collection (Senbil and Kitamura, 2009) can be reached easily, even with rather low monetary incentives.

When conducting such a smartphone-based collection of travel diaries over time, the validation behavior, i.e., whether a participant is validating or editing the entries in the travel diary and traveling abroad, is relevant for the overall design of the study as it has implications on sample size and data quality. Figure 6 shows the time series of the validation behavior and share of users abroad. For our sample, we find that around 60% to 70% of the sample were actively editing and validating entries, which is consistent with literature values (Molloy *et al.*, 2022). The

Figure 6: Insights into the panel behavior regarding validation of travel diary entries and travel abroad.

a) User validation behavior in the smartphone app per study month

b) Share of app users abroad per study month



share increased for both recruiting periods again after reminding them before the start of the "Deutschlandticket". After the last questionnaire in July 2023 and the last communication that the study ends now, with data collection continuing until December, the share drops similarly for both groups. The share of users abroad in our sample is between 5 and 10% with the peaks occurring during the summer holidays in August and September. We further find that the median cross-border trip length is between 200 and 300 kilometers, almost five times the average daily travel distance within Germany (Bundesministerium für Verkehr und digitale Infrastruktur, 2018); especially in smaller samples, these trips consequently require special attention, e.g., removal, to avoid single trips impacting the entire sample statistics.

5.2 Study completion

We consider a complete response of a respondent of each of the three panels as follows

- SR panel with app: completion of waves 1 to 3, 5, and 6 (we do not require completion of the fourth wave to be coherent with the ER panel) and providing at least one travel diary

Table 1: Gender and age distribution of all three panels for those participants who completed the study. Differences to 100% result from rounding as well as persons who did not wish to disclose their gender or identify themselves with one of the two genders provided in the table.

		Males			Females		
Total share		SR (47.7%)	ER (55.5%)	SR w. app (53.5%)	SR (42.4%)	ER (43.9%)	SR w. app (45.5%)
Age	18-24	1.2%	4.0%	11.0%	6.5%	3.8%	9.76%
	25-34	15.1%	14.5%	24.8%	10.4%	19.0%	26.3%
	35-44	17.4%	18.5%	19.1%	22.1%	21.5%	18.6%
	45-54	15.1%	19.6%	15.0%	15.6%	21.5%	20.7%
	55-64	12.8%	27.9%	16.4%	28.57%	24.1%	17.5%
	65-99	38.4%	15.6%	13.7%	16.9%	10.1%	7.1%

entry before, during, and after the "9-Euro-Ticket" as well as at least one travel diary entry before and after the introduction of the "Deutschlandticket". Note that participants who joined the study in the second recruiting period or left after the "9-Euro-Ticket" are also considered to have completed the study when they completed the relevant tasks during their study participation.

- SR panel (without app): completion of waves 1 to 3; participants in this panel were not invited to the last three waves.
- ER panel (without app): completion of waves 1 to 3, 5, and 6; participants in this were not invited to the fourth wave.

Based on these criteria, we find that 479 participants (42.0%) completed the SR panel with the smartphone app, 163 (28.8%) completed the SR panel, and 435 (47.4%) completed the ER panel. When relaxing the criterion of one travel diary entry before the start of the "9-Euro-Ticket", which is reasonable considering the short time before the start of the "9-Euro-Ticket" we find that 754 participants of the SR panel with the smartphone app (66.1%) completed this panel. The SR panel without the smartphone app was completed by 163 participants (28.7%), and the ER panel was completed by 435 participants (47.4%). Break down of completion numbers by the three SR panel subgroups (in parenthesis the completion when relaxing the criterion of one travel diary entry before the "9-Euro-Ticket"): 218 (317) in the "all" group, 106 (228) in the "net" and 155 in the "dt" group. For all who completed the study, Table 1 compares gender and age by panel. Here, we find that the substantially lower share of females in all three panels, as well as oversampling, in particular younger people in the SR panel with app, while the SR panel has a higher share of older people.

6 Lessons learned

The complex study design (see Figure 1) with six questionnaires and semi-passive travel diary generation based on GPS tracking has no precedent in the German context, only the MOBIS study during the COVID-19 pandemic is similar in size and duration (Molloy *et al.*, 2022). Hence, many lessons were learned from the survey and tracking.

6.1 Survey data

The long panel duration, which was not anticipated at the beginning of the study, motivated us to include questions on changes in relevant socio-economic attributes such as household location, income, and employment status in the fifth wave. As many changes were reported, the lesson learned was to integrate a dedicated section on this aspect in every panel wave, which is also helpful for studying time use and monetary expenses together with the travel diary data. Similarly, we initially used travel behavior scales from Germany's pre-pandemic household travel survey (Bundesministerium für Verkehr und digitale Infrastruktur, 2018), which we enriched and altered over time as we were concerned that post-pandemic variance in travel was not adequately captured. These changes here, of course, interfered with consistency in the survey items and, hence, data quality. On the contrary, questions that can be easily replaced with the smartphone-based travel diary were not removed from the questionnaire. Thus, the lesson learned here was to invest more resources in optimizing questions to maximize information in the post-pandemic and smartphone-based world. Last, we expect effects of social desirability in the data, e.g., people stating more public transport use with the fare innovations; here, we found it useful to ask respondents the same question twice and also use these kinds of questions as attention checks for data validity.

6.2 Tracking data

The quality of the tracking data largely depends on the involvement and attentiveness of the participants. Here, the trade-off is whether to request the participants to report more information or to lower the burden as much as possible. The former would ensure higher-quality data, while the latter would reduce the risk of people abandoning the experiment. The lesson learned was that the simple travel diary used worked surprisingly well, but a smart, and interactive app design, eventually with gamification, could make it more enjoyable for participants to edit and

validate the entries in the travel diary. For example, participants may only be asked to validate difficult-to-identify trips or new trips, i.e., trips that have never been done before. Further, we find that some participants do not report a home location, which may result from the users' poor involvement. This can be rectified to some extent based on post-processing tracking data (Gao *et al.*, 2021; Montini *et al.*, 2014) or survey data, we asked for the zip code, but this information is so crucial that the lesson learned was to be prepared for this situation in advance in the study design, e.g., via direct in-app notification to these participants, or making the reward conditional to the provision of this information. This not only applies to the home location but also to other frequently visited locations.

The aspect of the locations is also relevant for the chosen mode and time use. The complexity and similarity of available transport modes, e.g., car vs. ride-sharing, poses important challenges to the GPS-based mode imputation algorithms due to the similar characteristics between modes (in terms of speed, used infrastructure, etc.) (Nikolic and Bierlaire, 2017). If not labeled properly by the user's validation, this information might be partially obtained in the post-processing (Reck *et al.*, 2021). Similarly, measurement errors in the smartphone, e.g., missing activities or trips, sometimes happen, which implies that one can no longer derive trips or accurately analyze this person's day. Here, the lesson learned is that if the study design anticipates this and asks participants for missing relevant trips and activities, e.g., frequently done or a completely new one, to provide such information, the data quality would be drastically improved.

7 Recommendations for study design

Generally, it is important to be strategic when designing a study. The overall response burden must be carefully considered and to which extent the user should be involved in the app (Schmid and Axhausen, 2019; Lynch *et al.*, 2019). Although the app promises, in theory, high-quality travel diary data with GPS precision in space and time, data quality issues are present in practice. Hence, priorities regarding the desired information to be collected should be at the core of the study design, e.g., trip rates, travel distance, mode choice, time use, etc. As found in our study, but also as reported in literature (Winkler *et al.*, 2022), providing a monetary incentive can improve study participation and data quality, but here, our recommendation is to link this not only to temporal participation but also to validation activity.

Regarding recruiting, the "Mobilität.Leben" study is unique as we had only a short time period

between when the "9-Euro-Ticket" passed parliament and its starting date. This did not allow for a conventional recruiting strategy resulting in a representative sample, but in a convenience sample (see Loder *et al.* (2022); Cantner *et al.* (2022) for a discussion and biases). Nevertheless, despite the short time period, recruiting and onboarding went smoothly, and within two weeks, a majority of first-period recruits were actively tracking, suggesting that this can be successfully repeated for other studies. It can be expected to be challenging to perform the recruiting via a third party that delivers a representative sample for such long tracking studies. We recommend researchers do a multi-level, multi-channel recruiting, using mail-in letters, social media, and public media channels to attract as many as possible to register for the study and then select from this the sample.

Using an integrated survey comprising multiple questionnaires and GPS tracking leads to a complex data structure with quite heterogeneous data quality in the collected travel diaries, which one should be aware of; here, in particular, the travel diary data quality can be influenced by users' validation behavior and from the smartphone's operating system (Molloy *et al.*, 2022). Regarding the data quality, using attention checks in the survey and questions to validate the survey data with the travel diary data from the smartphone could improve data quality as inconsistent responses can be removed. As mentioned earlier, using monetary incentives and some post-processing of the travel diary data can improve the quality, but one should be aware that all of these approaches are resource- and time-expensive as no standard automation exists so far.

At the first participation peak in the smartphone app in June 2022 (see Figure 4, we received around five to ten emails per week from participants asking for support in the app activation, for setting the correct app parameters, or were reporting errors in the tracking, e.g., gaps in the travel diary. While this amount is not overwhelming, it must be factored into the panel management resources to satisfy participants. Here, future studies could benefit, e.g., from having video documentation on activating and using the travel diary instead of a written FAQ. Given the more or less similar recruiting strategy in both periods, there are substantial differences in registration and app activating numbers as well as study completion and attrition rates between both groups from the different recruiting periods: participants from the first recruiting period always performed better. This can be attributed to the compensation paid to the sample recruited in the first phase and presumably a higher (altruistic) motivation to contribute to "9-Euro-Ticket" research, which was widely discussed in public.

8 Conclusions

In this paper, we presented our survey to observe two large-scale nationwide public transport pricing experiments: the “9-Euro-Ticket” and the “Deutschlandticket”. Our survey method integrates questionnaires with a smartphone app for a semi-passive travel diary collection. We have shown that it is possible to conduct a 20-month-long panel study using such a smartphone-based approach. Overall, we recruited 2,624 participants, of which 1,140 used the smartphone-based travel diary generation; 62% of respondents completed all questionnaires to which we invited them; 218 participants completed the survey as well as provided travel diary entries from before the introduction of the “9-Euro-Ticket” until after the introduction of the “Deutschlandticket”.

There are not many similar panel tracking studies in terms of sample size and duration. Most likely, only the MOBIS/COVID study from Switzerland includes more than a thousand participants over almost three years (Molloy *et al.*, 2022) and the AKTA road pricing experiment from Denmark that includes 500 participants over around 100 days (Nielsen and Sørensen, 2008) are comparable, while the latter uses GPS trackers instead of a semi-passive travel diary. Consequently, as MOBIS/COVID and “Mobilität.Leben” are studies that have been established under exceptional circumstances, the implication for future research is to investigate how such large panel studies can be successfully conducted, made reproducible and valuable, e.g., for household travel surveys and randomized control trials to investigate travel behavior changes in response to (transport) policy stimuli. Nevertheless, for such surveys, the study duration must not be in the order of years, but rather in weeks as seen in other projects’ study duration, e.g., the three-week period of the “Lake Geneva Sustainability Monitoring Panel” (EPFL, 2023) and the six-week period of “Mobidrive” (Haupt *et al.*, 2001), or the two-weeks period suggested by (Senbil and Kitamura, 2009), which reduces data collection cost and risk of user attrition substantially. On the methodological side, however, future research must develop methods to obtain the information needed from such week-long semi-passive travel diaries, e.g., methods to separate habitual and regular from irregular travel patterns. This could then be used to ask app users selectively to edit and validate the latter trips when they provide more information. In addition, developing further post-processing methods to enrich the travel diary data and reduce the errors from the measurements, e.g., by continuing the work (Dahmen *et al.*, 2024), are part of future research.

In closing, while the survey method of “Mobilität.Leben” seems promising and powerful to reveal the complexity of spatiotemporal effects associated with the public transport fare policy innovations of the “9-Euro-Ticket” and the “Deutschlandticket”, so for any other large-scale transport policy intervention, the complexity and costs of conducting such a survey are undeni-

able. Further, many methods to reveal and estimate the effects are still under development, or existing ones require adjustment and testing. Consequently, the still-to-be-answered research question remains: to what degree would such a study lead to more information and insights, especially when facing budget constraints? Considering that artificial intelligence is improving mode and activity detection while the digital literacy of participants is increasing from year to year, both reducing costs and increasing data quality, the probability of a "yes" answer to that research question will increase over time.

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10 Author contributions

The authors confirm their contribution to the paper as follows: study conception and design: Allister Loder, Klaus Bogenberger; data collection: Allister Loder, Fabienne Cantner; analysis and interpretation of results: Allister Loder, Fabienne Cantner, Victoria Dahmen, Isabella Waldorf, Santiago Álvarez-Ossorio, Klaus Bogenberger; draft manuscript preparation: Allister Loder, Victoria Dahmen, Isabella Waldorf, Santiago Álvarez-Ossorio. All authors reviewed the results and approved the final version of the manuscript.

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