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TimeUse+
A Multi-Layered Travel and Time-Use Diary Format

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ABSTRACT

The latest travel behavior modelling frameworks consider travel decisions as part of a general time- and expenditure allocation problem. Their estimation consequently not only relies on large amounts of travel data, but also on information about time-use and expenditure allocation patterns. We present the TimeUse+ Platform, a novel data collection method based on state-of-the-art GPS-tracking technology. Our approach combines a travel and a time-use diary format into one comprehensive survey design. This multi-layered diary format allows to collect more accurate and complete data when compared to previous work which is solely based on traditional paper-based survey methods. This paper gives a detailed overview about the main components of the TimeUse+ Platform. We derive requirements from the current state in smartphone-based survey methods and travel behavior modelling, and show how the different design aspects of our solution fulfill those.

Keywords: Travel behavior, Travel diary, Time-use diary, Expenditure diary

INTRODUCTION

A considerable part of research in transport modelling focuses on estimating transport-related time valuation metrics like the Value of Travel Time Savings (VTTS). The VTTS has a wide application to policy making when prioritizing governmental funding. It represents the value of time reduced from travel and is typically estimated using Discrete Choice Models. Those allow to empirically derive the VTTS from observed travel choice data as willingness-to-pay for reduced travel time (1). The underlying micro-economic framework formulates travel decisions into a general time allocation problem, in which individuals not only maximize the utility from an independent travel-related decision, but also from those in the surrounding time- and expenditure-space (2). A prominent framework was presented by Jara-Diaz (3, 4) and defines the value of leisure (VoL), which represents the utility of activities to which more time than necessary is allocated, as sum of the VTTS and the value of time assigned to travel (VTAT). This decomposition of the VoL allows for a deeper exploration of the time-money trade-off in travel decisions. It provides a way to analyze mode-specific travel conditions, which is of particular interest when evaluating existing and specifically emerging mobility products in a policy-making context (5).

While this framework has seen wide acceptance in the scientific community, only limited amount of surveys have tried to estimate the corresponding models to a complete extent. This is due to the large amount of required data, which includes information about travel choices, as well as expenditure and activity allocation patterns. An overview about all published models based on the Jara-Diaz framework with the corresponding datasets used for their estimation is given in (6). Thereof, only the PCW (6) and MAED (7) dataset have actually recorded the three required dimensions for the same respondents. Early works address the lack of appropriate data by merging different datasets which comes with somewhat problematic statistical assumptions and typically decreases the time- and expense-resolution of these synthetic datasets. This lack of datasets can to some extent be explained by an associated lack of efficient data collection methods. Both mentioned datasets have been collected using resource-intensive mailback-surveys. Considering the recent developments regarding travel- and mutually-related time-use survey methods, this exhibits clear disadvantages and does not leverage the latest, specifically smartphone-driven, technological possibilities. Smartphone apps have the advantage to passively collect data, and GPS-tracking has evolved into the most relevant data collection tool for surveys in transport modelling (8). The travel and time-use research community consequently widely adopted smartphone apps for diary collection. Even-though latest travel and time-use diaries have been showing a growing overlap in data of interest and applied methods, there is currently no smartphone-app that fully merges both diary formats and additionally enables to record information on expenditure patterns.

The advances in econometric travel choice modelling hence lack suited data collection methods in order to be fully applied to real-world transportation problems. This research gap is the core interest of this paper. We present the TimeUse+ Platform, which consists of the TimeUse+ App, a WebAdmin interface, and a state-of-the-art GPS-tracking pipeline for automated diary generation. The TimeUse+ App uses a multi-layered diary format which fully integrates a travel, time-use and expenditure diary. Various generic aspects can be configured and allow to control which specific data fields are considered for a given survey, and through which collection mechanism those are recorded. This not only allows to cover a wide range of survey use-cases, but also to test aspects of the user interaction which relate to the data collection task and have significant impact on the response burden. We describe the development process of the platform, giving detailed information about how different requirements arise from the a modelling and survey method per-

spective. We show how these requirements translate into essential design aspects, and additionally give an overview about our underlying GPS-tracking pipeline.

COMBINING TRAVEL, TIME-USE AND EXPENDITURE DIARY SURVEYS

One of the on-going challenges in travel-choice modelling is the combination of discrete travel-choice models with continuous time and budget allocation models. The challenge is two-sided, one consisting of merging both types of models into one framework which is aligned with micro-economic theory, the other consisting of collecting the required data (9). While this paper does not focus on modelling frameworks, considering a specific model formulation from (7) illustrates the three dimensions of data required for such type of models:

$$U = \theta_w log(T_w) + \sum_{i=1}^{n} \theta_i log(T_i) + \sum_{j=1}^{m} \varphi_j log(E_j) \tag{1}$$

Equation 1 shows the log-version of a Cobb-Douglas production function that represents the utility function of an individual. It constitutes three different utility components arising from work, time assignments and good consumption. The θ_w, θ_i and φ_j parameter describe the respective base utilities. A corresponding data collection method needs to capture the time allocated to work (T_w), the time allocated to non-work activities (T_i), and finally the expenditures (E_j). The non-work activities consist of travel, leisure and so-called constrained activities, to which a certain amount of allocated time is indispensable (e.g. personal care). Accordingly, the expenditures must be differentiated into so-called constrained or unconstrained goods, with the former representing indispensable expenses, and the latter freely-assigned ones. The different data on travel and non-travel activities, as well as on the expenditures are subject of the three traditionally independent research fields on travel, time-use and expenditure modelling. The previously mentioned PCW and MAED datasets are the only published datasets which merge these three types of data into one comprehensive survey. Both datasets are however based on traditional, self-reported diary methods. Especially the travel and time-use research field have recently seen a wide application of smartphone-apps, as those allow to collect numerous sorts of data in an automated manner. Compared to traditional methods, they provide the possibility to interact with survey participants in multiple ways to actively collect additional self-reported data (10). Furthermore, they allow to tailor the user engagement to address well-known diary survey problems like user retention, non-response and information recall, which are specifically relevant to long-duration studies (11).

Travel and time-use diary surveys

Travel diaries record the trips a survey participant conducts each day. When conducted by national governments, they typically cover a period of multiple days up to one week. Relevant data-fields on a trip-level usually, but not exclusively, include start and destination, departure and arrival time as well as transport mode and trip purpose (12). Apart from national guidelines, there are no widely accepted official travel survey standards (9). The recorded travel purpose can for instance refer to activities or specific places (e.g. shopping or home). The core travel data is usually enriched with contextual information on a trip-level to evaluate on recent research trends. Those include delivery-related behavior (6), social contexts (13, 14), joint-decision making (15, 16), as well as subjective travel experience and travel-based multitasking (17, 18). Time-use diaries record the activities a survey participant performs each day. Common diary formats segment each day's 24 hours into a discretized timeline of 10-15 minutes slots and typically record up to seven days of

data per respondent. For each of those slots, respondents are asked to specify the current activity including contextual information about the activity location or participating persons (19). Travel is considered as activity and hence included, while not with the same level of detail as in travel surveys. Time-use diaries have a strong interdisciplinary character and are used in many different research fields (e.g. health or social sciences) and hence come in a wide range of formats. Over the last decades, national agencies have synthesized standards like the guidelines on Harmonized European Time Use Surveys (HETUS) (20). They for instance recommend using self-reported mailback-surveys, fixed intervals of 10 minutes and a survey period of two days.

The research fields on travel and time-use diary surveys can be considered to be mutually correlated. Travel decisions are generally modeled using activity-based approaches, which consider travel as an activity itself (21). Travel diaries hence collect non-travel related information like e.g. the trip purpose which relate to the activities motivating the trip. On the other hand, time-use diaries also include travel activities, and consequently collect at least the geo-spatial metadata of trips. This shared interest in the same types of data translates into similar developed smartphone-apps and technologies (22). The availability of assisted GPS in combination with additional smartphone sensory data (e.g. accelerometer, gyrometer) and external data sources (e.g. map data) became of specific interest for both respective data collection tasks due to the large potential to automate the diary generation. These technological advances have helped to reduce well-known travel and time-use survey problems like oversimplification and under-reporting of (specifically short) trips/activities as well as imprecise reporting of times and locations (23). An overview about latest smartphone-based travel and time-use diary survey platforms is given in (24) and (19) respectively. Although smartphone-apps from both fields rely on similar technological features, no current solution has so far fully integrated both diary structures into one comprehensive diary format. The work of (10) uses the rMove App to generate an automated travel diary, and an additional web-interface for the user to provide information about activities performed at home. The time-use component hence does not cover a full 24 hours and misses a significant portion of a full time-use format. The work of (23) uses the Future-Mobility-Sensing Platform and collects a travel- and time-use diary. Both diaries are however recorded individually from each other using a smartphone-app for the former, and a web-app for the latter.

Expenditure diary surveys

Expenditure surveys aim to collect data about financial behavior and spending patterns. They are used in a wide range of economic and social research fields, and are typically conducted on a regularly basis by national governments (25). Relevant data include balances, financial holding, income and expenditures. Diary formats are typically used as part of larger surveys and usually function as record-keeper for short-term, reoccurring expenses (9). All expenses are usually allocated to predefined expense classes from official guidelines like in (26). As opposed to the travel and time-use research area, this scientific field has seen only few smartphone-apps being developed. This is mostly due to the fact, that there is little potential for automated data collection and the manual reporting of detailed expenditure information is highly burdensome (27). The work of (28) and (27) use smartphone-apps to scan receipts of daily expenses, and additionally report expenses without receipts and days without any expenses. The work of (29) analyzes different types of human behavioral data including mobility routines, social interactions and spending patterns. The data is recorded and collected using a smartphone-app that leverages GPS-tracking capabil-

ities. Even-though this approach combines a (reduced) travel diary with an expenditure diary, it does not include the time-use dimension and hence does not fill the research gap of this paper.

REQUIREMENTS

To address the previously discussed research gap, the main objective of the developed software is to provide a novel data collection method to record a joint travel, time-use and expenditure diary dataset. The platform shall include a smartphone-app that leverages the latest GPS-tracking technology to automate the travel-related diary generation. Following common software development practice, we derive relevant software requirements according to the quality attributes from ISO 9216 (30).

Suitability and Accuracy

The suitability and accuracy requirements cover the core functionalities of the developed smartphone-app. They can be segmented according to the stakeholders they are arising from. From a survey participant's perspective one must consider the specific user needs which participants have when committing to a given survey. While early travel diary smartphone-apps have focused on the core tracking and automatic diary generation functionalities, some more recent approaches like e.g. (17, 31, 32) have aimed to combine a wider range of user functionalities (trip planner, trip coaches or gamification approaches) which shall increase the user engagement and ultimately the resulting data quality. In the work of (17) which is the most similar to ours, the authors however identified only two relevant user needs, those being supporting the corresponding research and having access to dashboarding functions according to the Quantified-Self approach (32).

From a researcher's perspective, it is necessary to record the data required to estimate the model from Equation 1, as this is the main research gap this paper covers. The collection method must record a joint travel, time-use and expenditure diary, and allow the differentiation of activities and expenditures as described in section 2. Furthermore, the data must be recorded for the same person over a duration which can be considered representative of a long-term equilibrium (9, 4). While national travel- and time-use diary surveys typically consider a few days (up to one week) as sufficient, work like (33, 34) argue that longer survey periods are required to fully capture intra-personal variety and routines which span over multiple days/weeks. Expenditures diary surveys generally cover periods of up to 4 weeks, as buying patterns typically show strong weekly variation. The developed method, and specifically the smartphone-app, shall therefore be designed under the consideration to enable surveys over multiple weeks. The model of interest does not impose any requirements regarding the accuracy or completeness of the recorded data. In context of automated diary generation, the accuracy and completeness mainly related to the amount of trips/activities detected as well as the accuracy of the related data-fields (trip, mode, activity/purpose), both of which represent on-going research challenges.

The requirements mentioned in the previous paragraph are solely based on one specific modelling use-case. As the development of the corresponding data collection platform including the development of a smartphone-app requires significant monetary resources (35), an additional functional requirement placed upon the developed smartphone-app is that it can be applied to other relevant survey use-cases (see section 2). The relevant transport modes can for instance considerably change depending on the survey area, and the segmentation of activities and expenses can vary according to different official (national) guidelines. Furthermore, the previously mentioned research trends typically require specific data on a (travel) activity-level. This translates into the

necessity to be able to configure the smartphone-app for a given use-case and to control it's generic aspects.

Usability

The usability requirements include the understandability, learnability and attractiveness of the developed smartphone-app. These three factors have a large impact on the resulting response burden and user-behavior. They are hence crucial to ensure that respondents correctly report the data of interest with the required quality and granularity. The response burden is of specific relevance for our use-case which is only partly automated and requires large amount of user-reported data. The understandability and learnability can for instance be enhanced by using official guidelines on self-explanatory software design and the specific consideration of user-experience (UX) design findings (36). Push-notification are commonly used to remind the user to input, correct or validate data. Work like (37) suggests using tutorial videos as part of a larger on-boarding process. Work from (38) shows that design aspects like screen-size and format can have significant impact on the resulting data quality. The best-practices, and specifically those regarding the actual design of user-interfaces (UI), are however typically very distinct to the respective survey use-case and platform used. This emphasizes the necessity to test different design and UX aspects and to have the possibility to do so. The UX aspects which relate to the data reporting task include setting default values, enforcing or suppressing validation/correction of default or automatically filled values, changing the scale/granularity of requested data-fields as well as setting their specific UI control element (sliders, switches, pickers, menus, etc.). Using the time budget assessment scheme from (39), the relative effects those factors have on the response burden can be quantified, which is useful to compare different UX-design implementations. The travel data reporting task includes validating and correcting the data coming from the GPS-tracking pipeline. Its performance regarding completeness and accuracy hence also directly affects the resulting response burden.

Reliability and Efficiency

The reliability groups several requirements which relate to the operationability as well as the software's maturity and fault tolerance. The smartphone-app should ideally be operational on as many operating systems (OS) as possible in order not to enhance an already existing selection bias when using smartphone-apps (40). Common diary survey smartphone-apps however only focus on the two predominant OS from Apple and Google, as those cover most of the market, while the small shares of other OS do not justify the additional development efforts. The operationability is not only relevant to the software-, but also on the hardware-components. Especially the GPS-tracking pipelines are highly dependent on the device and the capabilities of its on-board sensory hardware (41). Recent studies conducted at IVT have shown significant differences between the mode detection performances of different OS and device combinations. It must hence be ensured that the developed smartphone-app shows comparable performance for the majority of common devices.

The requirements regarding efficiency is particularly relevant in context of energy usage. As retrieving GPS-traces requires comparably large amounts of energy, GPS-tracking smartphone-apps are notorious for draining the smartphone batteries (42). Optimizing the battery usage represent one of the major challenges which arise when developing GPS-tracking smartphone-apps, as it heavily influences the user-acceptance and -retention (43). It also directly correlated with the trip- and mode-detection performance as the corresponding algorithms work the better the more GPS-traces are available. The on-going advances in battery technology, sophisticated algorithms that

use fewer GPS-traces, and energy-optimized data transmission can however reduce those battery-related problems (37).

TIMEUSE+ PLATFORM

The TimeUse+ platform consists of two components which are illustrated in Figure 1. The TimeUse+ App is the core element of our developed method and records a joint travel, time-use, and expenditure diary. The App sends sensor data to the external MOTIONTAG API, which are then processed into a travel diary. Our integrated diary format is then constructed within the TimeUse+ API by merging the just mentioned travel diary, with time-use and expenditure diary components which are self-reported by the user and transmitted through the App. This merged data-stream is stored in a database and can be fetched from to the App for visualization. Furthermore, the App accesses a configuration file through the TimeUse+ API, which specifies various generic aspects of the survey format. This configuration file can be edited by the researcher through the WebAdmin, along with other survey management functionalities.

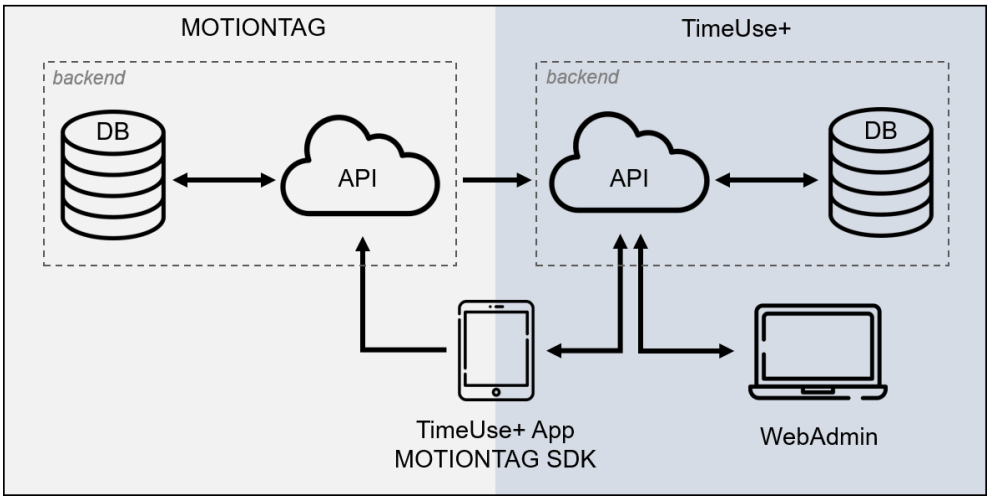


FIGURE 1: TimeUse+ Platform architecture.

MOTIONTAG SDK and API

The travel diary component of our multi-layered diary format is automated using the technology-stack from MOTIONTAG. The stack consists of two components: a Software-Development-Kit (SDK) which is implemented in the TimeUse+ App, and a backend that consists of an API and a database. The backend uses the raw sensor data transmitted by the SDK and performs the trip- and mode-detection. It then communicates the results back to the TimeUse+ App and the database.

The SDK enables the recording and processing of sensor data on the device and controls the transmission of the data to the MOTIONTAG backend. The SDK was designed to minimize the use of energy-intensive satellite-data in order to maximize the battery-efficiency. One approach to reduce battery consumption is the usage of other sensors whose battery consumption is lower. Apart from the localization data from satellite-based technology (GNSS) which is paired with WLAN and GSM positioning, the SDK therefore also records acceleration values, gyroscope values, the movement activity distributed by the OS (including WLAN and mobile phone networks), the detection reliability of the movement activity, and user agent information (device type, OS version,

app version). The raw GNSS sensor readings are filtered for outliers and smoothed in order to derive user-specific stages in the continuous stream of data. The data is enriched with geo-spatial data from the OpenStreetMap project and segmented into trips and stays depending whether targeted continuous movement is detected or not. The individual stages with all data-streams are then fed to a Deep Recurrent Neural Network (RNN). The RNN is trained to predict the transport mode of each stages, and additionally detects specific change points within a stage to account for multi-modal transport. Those change points are used to segment a trip into different triplegs. The predicted modes include 'walk', 'bicycle', 'motorized', and 'rail'. The mode detection achieves accuracies of approx. 90 %.

The SDK is provided for iOS and Android individually. Although the basic functionalities and methods are similar on both platforms, a hybrid development approach is not possible, since specific features of the operating systems have to be considered. This is mostly relevant in context of the distribution of location data which is managed by different services on Android and iOS. It requires that different wake-up and fall-asleep-logics have to be implemented, in order to ensure the operationability across both platforms. The proper access to all relevant sensor data on both OS types is crucial for an energy-optimized operation of the mode detection pipeline.

The resulting diary format which is provided to the TimeUse+ App through the MOTIONTAG API consists of a continuous chain of *triplegs* and *stays*. For both of these event types, the API provides information about start and end time as well as timezone and location geometry. Triplegs additionally include the mode which gets automatically detected as well as the distance traveled. Stays are characterized by their type which has to be reported by the user at any first visit. These types (e.g. at home, at work) are predefined by the app environment and subject to a routine detection which automatically assigns the stay type when the user visits the location again.

TimeUse+ App

The key functional aspect of the TimeUse+ App lies in its underlying diary format which fully integrates a travel and a time-use diary. Figure 2 depicts the time-axis of the two individual and the integrated diary format. It illustrates how activities are mapped to the time-axis for an simplified exemplary day like given in axis (a). The exemplary day consists of travel and non-travel activities. The "travel + work" activity describes someone that is working while simultaneously traveling, e.g. in a train. It is included as it illustrates the previously mentioned research on multitasking, but also because it shows the problem of correctly capturing the time allocated to work in context of the model formulation in Equation 1.

Axis (b) corresponds to a time-use diary format with its discretized time-axis, where each time-slot is allocated to one activity. Activities with durations smaller than the resolution are not captured, and the discretization of the timeline results in inaccuracies. Axis (c) corresponds to a travel diary format, like the one used by the MOTIONTAG API. The time-axis is continuous and non-travel activities are partly captured through the reported trip purpose. Other activities between two trips as well as during trips cannot be captured. Axis (d) represents our multi-layered integrated diary format. The first layer corresponds to a travel diary format and segments the timeline into a chain of so-called *events*. Events are referred to as *stays* if the user location is constant (blue segment), and as *trips* if not (grey segment). Stays are characterized by a location-type attribute (e.g. home, work, other, etc.), while trips are characterized by a transport mode-type attribute (e.g. walk, bike, car, train, bus, etc.). The second layer corresponds to a time-use diary format and segments each event into a chain of so-called *activities*. These activities are in turn characterized

by a set of *attributes* (e.g. duration, expenditures, etc.). The attributes can be used implement the expenditure diary functionality, thus covering the three data-streams required for our modelling use-case. Each point in time is consequently defined by the event type, the event metadata, the activity type, the activity metadata, as well as the activity attributes.

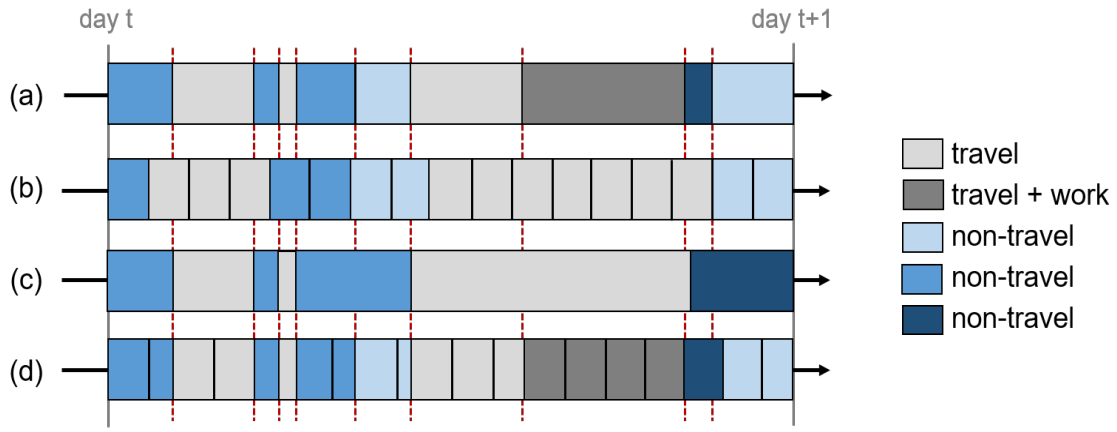
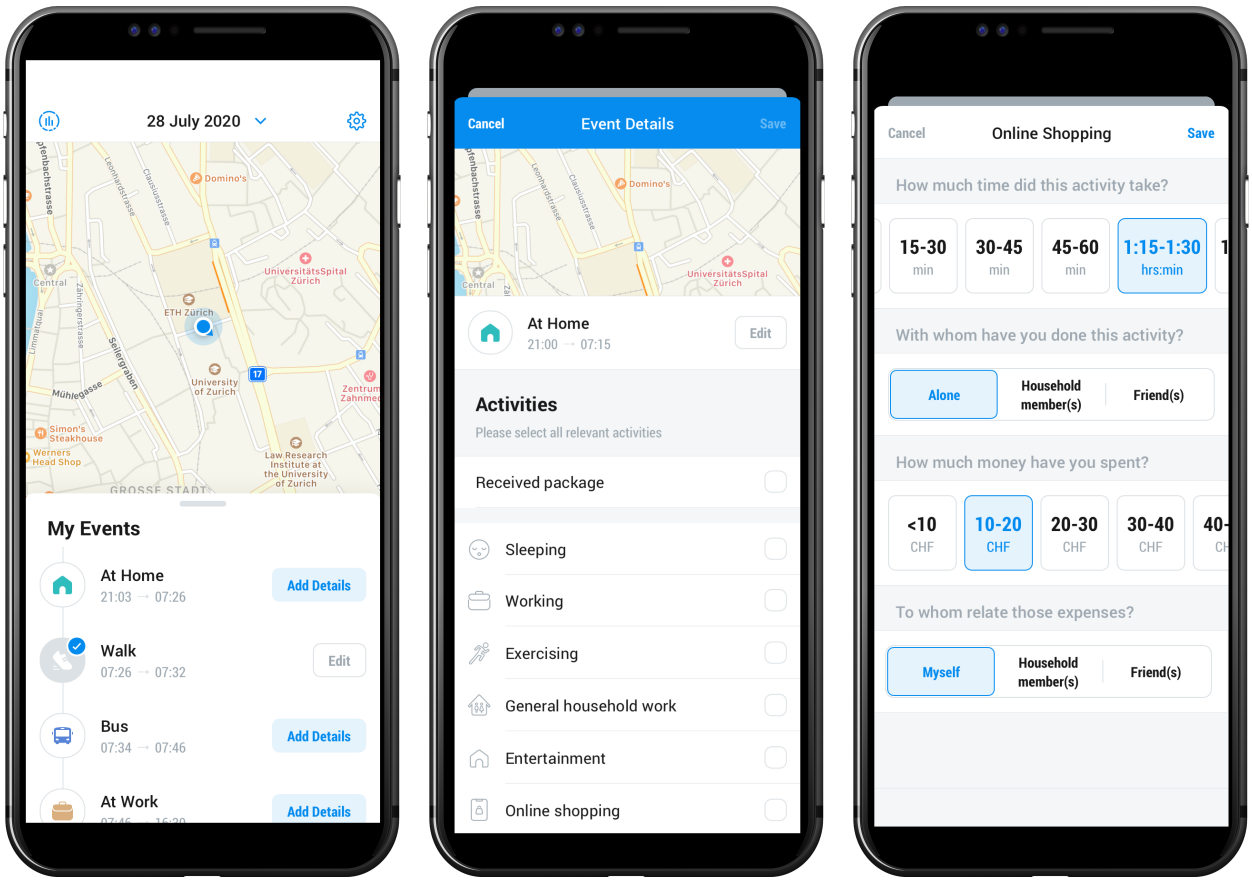


FIGURE 2: Activity allocation in selected diary formats: (a) exemplary chain of activities, (b) time-use, (c) travel, MOTIONTAG, (d) merged, TimeUse+.

Our platform allows to define the set of relevant event types, activity types and activity attributes which shall be used for a given survey and are dynamically retrieved through TimeUse+ API using the configuration file. One can for instance incorporate certain transport modes to represent a regional transport mode-mix, while segmenting the activities and expenditures based on official guidelines. Furthermore, a set of valid combinations of events and activities as of activities and respective attributes, can be defined. This permits to exclude unlikely combinations (e.g. sleeping while at work), but also to include specific activities of interest on conditional occasions (e.g. online shopping activity during an autonomous taxi ride).

Another aspect of the generic design lies in the possibility to map the data-fields of both layers to individual data sources and collection mechanisms. For our use-case, the data of the event-layer is mapped to the corresponding MOTIONTAG API endpoints (triplegs and stays), while the data from the activity-layer is mapped to manual user input. The provided transport mode is for instance mapped to the mode-type attribute of trip events. It is however also possible to merge certain mode- and location-types or to map additional ones to manual user input. The time and location-geometry data of activities and events are subject to rule-based automation that ensures the continuity of the location- and time-axis in both diary layers (e.g. event with one activity). While the data-fields provided by external APIs can be conditioned to have the possibility to be corrected by users, the just mentioned rule-based automation is not editable by the user. Finally our platforms also allows to define default values for each of the non-automated data-fields of both layers (e.g. default activities for a certain location type, or default attributes for a certain activity) and to enforce if certain values have to be specified or can be left unanswered in order to validate the respective day or event.

Subfigure (a) represents the home screen which appears when the (logged-in) user opens the app. The control-bar on top of the screen allows to open a calendar view to change the selected day, and includes buttons to open the dashboard and settings screen. The calendar overview vi-



(a) Home screen (b) Event-detail screen (c) Activity-detail screen

FIGURE 3: Screen mock-ups of the TimeUse+ App.

sually indicates the user about days for which data reporting is still required. The settings screen allows the user to access general settings, the FAQ section as well as to control the battery saving mode. The home screen displays the timeline of the current day with a corresponding map section. Previous surveys conducted using the Catch-my-Day App revealed a lower correction-rate of up to 20% for Android phone users. Both OS versions differ in the sense that the Android version only includes a map section, but not a timeline with an overview about recorded events. The rest of the structure and navigation between screens is the same, indicating that the timeline overview makes the reporting UI more intuitive for the user. This is further aligned with findings from (44) and (45), which state that recall methods based on a continuous consideration of all daily events (as opposed to just considering trips) perform significantly better. The timeline shows all recorded events with their start- and end-time, and visually indicates between stays and trips, and if an event has been validated yet or not. Placeholders are inserted in case of a malfunctioning external API to ensure the timeline continuity and to avoid disturbing the user. The timeline covers full 24 hours starting midnight each day. However, the first and last listed event can stretch into the previous or next respective day for better overview and to avoid a doubled reporting task for the users.

When tapping a specific event in the timeline, the map focus changes accordingly and the user can open a separate screen with the details of that event, shown in Subfigure (b). The event-detail screen shows a map section which corresponds to the respective event and allows to

correct the transport mode or location type respectively. The event-detail screen also shows a list of activities which can be selected by the user. The first section of the list hereby includes so-called *binary activities*, which are a simplified version of the regular activities previously defined but without any attributes. This provides a useful additional feature to collect data of interest on the activity-level (e.g. binary questions), without the user having to provide a full range of attributes on another screen. From the previously mentioned rule-based logic which ensures the continuity of both diary layer, follows that users have to specify at least one activity per event. If needed, the response burden can be lowered by setting a default placeholder activity (e.g. fixed duration placeholder for sleeping every day). The bottom of the page includes a button which allows users to delete a specific event in order to be compliant with potential data-privacy regulations.

Subfigure (c) shows this activity-detail screen which allows to specify attributes. An attribute is formally defined as set of questions with predefined answer values. The answers are displayed and selected using so-called segmented controls. As opposed to drop-down menus or pickers, segmented controls are rather simple and require a minimum amount of clicks. They further allow to represent a wide range of different answer formats while keeping the complexity of the generic functionality manageable. Our use-case does not require to know the order of activity, which is why we only ask for the duration. The screen can however also include two separate questions for start- and end-time. The design furthermore allows to control the resolution of the time and expenditure scales. Both could technically be realized as pseudo-continuous, most use-cases however do not require this level of detail.

TimeUse+ WebAdmin

The TimeUse+ WebAdmin is a web-app which provides the central UI for the researcher. It allows to control the generic aspects of the TimeUse+ App and to configure specific survey designs through a configuration file. This includes specifying all relevant event- and activity-types as well as activity attributes, their valid combinations, and finally the mapping of both diary layers to a data-source and/or collection mechanism. Apart from the specific survey design, the researchers can also control the push-notification functionality and the questions displayed on the FAQ screen. The former includes sending automated validation reminders based on a specified number of days without user validation or prompting the user to verify the GPS-access rights based on a number of days without receiving tracking data. Furthermore, push-notifications can be conditioned on certain activities and used to redirect the user to external mini-surveys or communicate relevant survey information.

Apart from controlling the generic aspects of the survey, the WebAdmin includes further functionalities to monitor and manage surveys and users. The sign-up process is based on invitation codes which users have to provide in addition to an email address when opening the TimeUse+ App for the first time. Invitation codes can be generated through the WebAdmin and extracted for distribution. The WebAdmin provides an overview about which invitation codes have been used and maps those to the corresponding email address of users if these signed up. The current tracking and validation status can be monitored for each user allowing for detailed analysis and targeted communication. Finally, the collected data can be filtered and downloaded in a csv-format for further processing.

CONCLUSION

This work contributes to the field of travel and time-use diary survey methods as well as to latest transport modelling frameworks which rely on those for data collection. While smartphone-apps from both research fields show a growing overlap in data of interest and applied technologies, we are the first ones to fully merge both individual survey types into one comprehensive multi-layered diary format. A high-resolution geo-spatial timeline is provided through a state-of-the-art automated travel diary generation pipeline, and is enriched with time-use and expenditure information provided by the respondents. The resulting joint travel, time-use and expenditure dataset can be applied to the most recent time valuation frameworks like presented in chapter 2. The resulting dataset can be expected to provide more accurate and complete data than existing work, which are based on traditional paper-based survey methods. This ultimately leads to more accurate estimates for policy-relevant time valuation metrics, and greater insights into the economic valuation of mode-specific travel conditions. Said multi-layered diary format is implemented in a generic manner, enabling researcher to configure the data-fields relevant to the travel, time-use and expenditure diary component, as well as their valid combinations. This makes our platform applicable to wide range of current research trends, where the underlying modelling frameworks typically impose narrow data requirements.

The TimeUse+ App has user-centric design and is based on self-explanatory software guidelines as well as synthesized findings from comparable works, including the Catch-my-Day App which was previously used by our research group. These findings emphasize concrete design features like the fundamental app structure and navigation but also stress the necessity to test different aspects of the UI and UX, especially those relating to the data reporting task. The generic functionalities of our platform allow to specify those aspects, hence giving researchers the possibility to derive an app-design which maximizes the data quality for a given use-case, but also to investigate how UX-design aspects affect user validation behavior in general.

Apart from its obvious scientific contributions, our developed data collection method however exhibits foreseeable drawbacks and challenges. The battery efficiency is only optimized from an algorithmic point of view within the MOTIONTAG SDK, the general problem of battery drainage remains, especially when older devices are used. Other problems like device specific performance fluctuation of the GPS-tracking pipeline, as well as the general problem of sample representativeness, also persist. Finally, our smartphone-app combines three separate diary components which individually already have the problem of high response burden and low response rates. It is hence questionable to which degree the TimeUse+ App will be able to provide the expected data and by what means response burden becomes an issue.

REFERENCES

1. Juan de Dios Ortúzar and Luis G. Willumsen. *Modelling Transport*. John Wiley & Sons, 4th edition, 2012.
2. Allan C. DeSerpa. Microeconomic theory and the valuation of travel time: Some clarification. *Regional and Urban Economics*, 2:401 – 410, 1973.
3. Sergio R. Jara-Díaz and Cristián A. Guevara. Behind the subjective value of travel time savings: The perception of work, leisure, and travel from a joint mode choice activity model. *Journal of Transport Economics and Policy*, 37(1):29 – 46, 2003.
4. Sergio R. Jara-Diaz, Marcela A. Munizaga, Paulina Greeven, Reinaldo Guerra, and Kay W. Axhausen. Estimating the value of leisure from a time allocation model. *Transportation Research Part B*, 42(10):946 – 957, 2008.
5. Simona Jokubauskaitė, Reinhard Hössinger, Florian Aschauer, Regine Gerike, Sergio Jara-Díaz, Stefanie Peer, Basil Schmid, Kay W. Axhausen, and Friedrich Leisch. Advanced continuous-discrete model for joint time-use expenditure and mode choice estimation. *Transportation Research Part B*, 129:397 – 421, 2019.
6. Basil Schmid. *Connecting Time-Use, Travel and Shopping Behavior: Results of a Multi-Stage Household Survey*. PhD thesis, ETH Zurich, 2019.
7. Reinhard Hössinger, Florian Aschauer, Sergio R. Jara Díaz, Simona Jokubauskaite, Basil Schmid, Stefanie Peer, Kay W. Axhausen, and Regine Gerike. A joint time-assignment and expenditure-allocation model: Value of leisure and value of time assigned to travel for specific population segments. *Transportation*, 47:1439 – 1475, 2020.
8. Li Shen and Peter Stopher. Review of gps travel survey and gps data-processing methods. *Transport Reviews*, 34:316 – 334, 2014.
9. Florian Aschauer, Inka Rösel, Reinhard Hössinger, Heinz Brian Kreis, and Regine Gerike. Time use, mobility and expenditure: an innovative survey design for understanding individuals' trade-off processes. *Transportation*, 46(2):307–339, 2019.
10. Chiara Calastri, Romain Crastes, and Stephane Hess. We want it all: experiences from a survey seeking to capture social network structures, lifetime events and short-term travel and activity planning. *Transportation*, 47:175 – 201, 2018.
11. P Grunewald, M Diakonova, D Zilli, J Bernard, and A Matousek. What we do matters – a time-use app to capture energy relevant activities. European Council for an Energy Efficient Economy, 2017.
12. Jędrzej Gadziński. Perspectives of the use of smartphones in travel behaviour studies: Findings from a literature review and a pilot study. *Transportation Research Part C*, 88:74 – 86, 2018.
13. Jinhee Kim, Soora Rasouli, and Harry J. P. Timmermans. Social networks, social influence and activity-travel behaviour: a review of models and empirical evidence. *Transport Reviews*, 38(4):499 – 523, 2018.
14. Khandker M. N. Habib, Juan Antonio Carrasco, and Eric J. Miller. Social context of activity scheduling: Discrete–continuous model of relationship between "with whom" and episode start time and duration. *Transportation Research Record*, 2076(1):81 – 87, 2008.
15. Giancarlos Parady, Andreas Frei, Matthias Kowald, Sergio Guidon, Michael Wicki, Pauline Berg, Theo Arentze, H.J.P. Timmermans, Juan Carrasco, Barry Wellman, Kiyoshi Takami, Noboru Harata, and Kay Axhausen. A comparative study of contact frequencies among social network members in five countries. 2020.

16. Sivaramakrishnan Srinivasan and Chandra Bhat. Modeling household interactions in daily in-home and out-of-home maintenance activity participation. *Transportation*, 32:523 – 544, 2005.
17. Yannick Cornet, Merrill Barradale, João Bernardino, and Giuseppe Lugano. Worthwhile travel time: Design challenges of capturing the user experience by smartphone. 2019.
18. Rico Krueger, Taha H. Rashidi, and Joshua Auld. Preferences for travel-based multitasking: Evidence from a survey among public transit users in the chicago metropolitan area. *Transportation Research Part F*, 65:334 – 343, 2019.
19. Stella. Chatzitheochari, Kimberly Fisher, and Emily Gilbert. Using new technologies for time diary data collection: Instrument design and data quality findings from a mixed-mode pilot survey. *Social Indicators Research*, 137:379 – 390, 2018.
20. Eurostat. *Harmonised European Time Use Surveys (HETUS) 2018 Guidelines*. Publications Office of the European Union, Luxembourg, 2019.
21. Chandra Bhat and Frank Koppelman. *Activity-Based Modeling of Travel Demand*, volume 56, pages 35 – 61. 2003.
22. Anne Elevelt, Wim Bernasco, Peter Lugtig, Stijn Ruiter, and Vera Toepoel. Where you at? using gps locations in an electronic time use diary study to derive functional locations. *Social Science Computer Review*, 2019.
23. Bat hen Nahmias-Biran, Yafei Han, Shlomo Bekhor, Fang Zhao, Christopher Zegras, and Moshe Ben-Akiva. Enriching activity-based models using smartphone-based travel surveys. *Transportation Research Record*, 2672(42):280 – 291, 2018.
24. Adrian C. Prelipcean, Yusak O. Susilo, and Gyözö Gidófalvi. Collecting travel diaries: Current state of the art, best practices, and future research directions. *Transportation Research Procedia*, 32:155 – 166, 2018.
25. Chen Zhen, Justin L. Taylor, Mary K. Muth, and Ephraim Leibtag. Understanding Differences in Self-Reported Expenditures between Household Scanner Data and Diary Survey Data: A Comparison of Homescan and Consumer Expenditure Survey. *Applied Economic Perspectives and Policy*, 31(3):470–492, 2009.
26. Department for Economic and Social Affairs. *Classification of Individual Consumption According to Purpose (COICOP)*. United Nations, New York, 2018.
27. Annette Jäckle, Jonathan Burton, Mick P. Couper, and Carli Lessof. Participation in a mobile app survey to collect expenditure data as part of a large-scale probability household panel: coverage and participation rates and biases. *Survey Research Methods*, 13(1):23 – 44, 2019.
28. Brendan Read. Respondent burden in a mobile app: evidence from a shopping receipt scanning study. *Survey Research Methods*, 13(1):45 – 71, 2019.
29. Simone Centellegher, Marco De Nadai, Michele Caraviello, Chiara Leonardi, Michele Vescovi, Yusi Ramadian, Nuria Oliver, Fabio Pianesi, Alex Pentland, Fabrizio Antonelli, and Bruno Lepri. The mobile territorial lab: a multilayered and dynamic view on parents' daily lives. *EPJ Data Science*, 5, 2016.
30. ISO/IEC. *ISO/IEC 9126. Software engineering – Product quality*. ISO/IEC, 2001.
31. Grzegorz Sierpiński, Marcin Staniek, and Ireneusz Celiński. Travel behavior profiling using a trip planner. *Transportation Research Procedia*, 14:1743–1752, 12 2016.

32. Jerald Jariyasunant, Andre Carrel, Venkatesan Ekambaram, DJ Gaker, Thejovardhana Kote, Raja Sengupta, and Joan L. Walker. The quantified traveler: Using personal travel data to promote sustainable transport behavior, 2011.
33. Robert Schoenduwe, Michel G. Mueller, Anja Peters, and Martin Lanzendorf. Analysing mobility biographies with the life course calendar: a retrospective survey methodology for longitudinal data collection. *Journal of Transport Geography*, 42:98 – 109, 2015.
34. V. Saikumar Chalasani and Kay W. Axhausen. Mobidrive: A six week travel diary. *Travel Survey Metadata Series*, 2, 2005.
35. Zachary Patterson, Kyle Fitzsimmons, Stewart Jackson, and Takeshi Mukai. Itinerum: The open smartphone travel survey platform. *SoftwareX*, 10:100230, 2019.
36. Adrian Prelipcean and Toshiyuki Yamamoto. Workshop synthesis: New developments in travel diary collection systems based on smartphones and gps receivers. *Transportation Research Procedia*, 32:119 – 125, 2018.
37. Hamid Safi, Behrang Assemi, Mahmoud Mesbah, Luis Ferreira, and Mark Hickman. Design and implementation of a smartphone-based travel survey. *Transportation Research Record*, 2526(1):99 – 107, 2015.
38. Daniele Toninelli and Melanie Revilla. *How Mobile Device Screen Size Affects Data Collected in Web Surveys*. John Wiley Sons, Ltd, 2019.
39. Basil Schmid and Kay W. Axhausen. Predicting response rates further updated. 2019.
40. Stacey Bricka, Rajesh Paleti, and Chandra Bhat. An analysis of the factors influencing differences in survey-reported and gps-recorded trips. *Transportation Research Part C*, 21:67 – 88, 2010.
41. Chris Harding. *From Smartphone Apps to In-Person Data Collection: Modern and Cost-Effective Multimodal Travel Data Collection for Evidence-Based Planning*. PhD thesis, 2019.
42. Zachary Patterson and Kyle Fitzsimmons. Datamobile: Smartphone travel survey experiment. *Transportation Research Record*, 2594(1):35 – 43, 2016.
43. P.A. Gonzalez, J.S. Weinstein, Sean Barbeau, Miguel Labrador, Phil Winters, Nevine Georggi, and R. Perez. Automating mode detection for travel behaviour analysis by using global positioning systems enabled mobile phones and neural networks. *Intelligent Transport Systems, IET*, 4:37 – 49, 2010.
44. Roger Behrens and E Masaoe. Comparative experimental application of alternative travel diaries in cape town and dar es salaam. 2009.
45. Peter R. Stopher and Stephen P. Greaves. Household travel surveys: Where are we going? *Transportation Research Part A*, 41(5):367–381, 2007.