The More You Know: Digital Twins of Travelers

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Abstract. Despite increasing digitalization, rail operators and other mobility service providers often need more real-time information regarding the occupancy of trains and stations. Worse, only general assumptions regarding passengers' specific destinations, individual needs, and current and past experiences can be made. Digital Twins of Travelers (DTT) address the issue by holding real-time digital representations of passengers throughout their journey from start to destination. Being informed about a passenger's route instead of isolated sections enables customized real-time forecasts, accessibility information for each transfer location, and veridical updates about how much time may be spent there. For example, a traveler would benefit directly when parts of a journey must be rescheduled due to delays on the original route. When continuing with means of transportation different from those chosen initially, forecasts and other information can be immediately adapted to the new route. In the same scenario, mobility service providers would benefit by being informed about occupancy changes, allowing them to prioritize scheduled connections if necessary. DTT consist of a real-world twin, its digital counterpart, and an interchange component linking them. The digital twin represents how travelers experience current events, holds information regarding their individual itineraries' progress, and can exchange information with mobility service providers. DDT's purposes range from supporting passengers in real-time by providing information relevant to their journey milestones, analyzing the effect of events such as delays on the travel experience, to helping to align transport services with the existing demand.

Keywords: Human Digital Twins, Public Transport, Travel Experience, Demand Forecast, Knowledge Management.

1 Human Digital Twin Systems

Digital twins were initially conceived in the context of product lifecycle management (PLM), intended as a structured approach to the design, manufacturing, deployment, and maintenance of physical products. Grieves (2005; Grieves & Vickers, 2017) argued that successful PLM requires detailed knowledge of the product state at all times and that a continually updated digital representation of the product can provide this knowledge. In this conception, knowing the state of a digital twin is equal to knowing the state of the represented object. The digital twin allows for complete predictability of its physical counterpart because of a mechanism linking the digital twin's virtual space with the real-world twin's real space. The mechanism continuously updates the digital twin, enabling data-generating processes like forecasts and analytics whose results may flow back toward the real space.

The core idea of coupled virtual representations of physical objects has received much attention, particularly in domains where product-related processes generate detailed yet isolated data (Liu et al., 2021). However, the purposes of digital twins have been explored beyond their original conceptualization, precluding uniform definitions of what such twins may encompass. Sjarov et al. (2020) suggested a purpose-related classification with two dimensions. The first dimension differentiates between an intended use for exploratory purposes, where no information flows from the virtual to the real space, and an intended use for decision-taking, where such information flows are characteristic. The second dimension differentiates between three kinds of entities the digital twin can represent. The first kind of representation concerns types instead of specific instances, for example, to enable virtual testing. The second kind represents individual instances, such as those required to track the life of a specific resource. The third kind of representation addresses more general system properties like resource consumption.

In recent years, the application of the digital twin concept to humans and human-related processes has been discussed. Building on use cases from medicine, ergonomics, or sports performance, Miller and Spatz (2022, Figure 2) suggested a general ontology of Human Digital Twin Systems (HDTS), comprising a real-world twin, its digital twin counterpart, and an interchange component linking both. Additional components, such as a visualization engine, can significantly enhance the system's effectiveness, particularly for exploratory purposes such as during the prototyping stages of system development. Minimally, the real-world twin comprises one human agent, one sensor to collect information regarding the current environment, and one process, such as a manufacturing workflow in which human behavior occurs. In the virtual world, the digital twin contains models of the human agent, the mission or task to be accomplished by the human agent, and performance goals to track how well the task is executed. Further, a prediction engine allows forecasting how changing properties within the virtual world would influence human or system performance, particularly regarding performance goals. Finally, the HDTS interchange component allows for bidirectional communication between the real and the virtual world and data-related functions such as persistent storage, cleaning, and fusion.

A critical difference between the concept of HDTS and PLM-related systems is the need to consider the enormous variety inherent to human experiences, human behavior, and the environments in which they occur. As Miller and Spatz (2022) pointed out, phenomena that need to be addressed include but are not limited to, the following items: (a) physical attributes such as biomechanical capabilities; (b) physiological states such as heart rate; (c) perceptual and cognitive performance capabilities such as knowledge and skills; (c) personality attributes such as traits; (d) emotional states such as uncertainty or frustration; (e) behavioral attributes such as actions taken in specific states of the environment.

In the case of physical products, many relevant attributes can be represented by measuring physical properties such as temperature. Precluding measurement errors, a user of the digital twin system can safely infer the real-world twin's state based on these measurements. In the case of human-related attributes, that is not necessarily the case. For example, based on an indicator such as a low heart rate, a person's stress level might also be classified as being low. However, such a classification can be substantially misleading without knowing that person's base rate. The relation between the level of indicator variables and the assumed level of human-related attributes is far less certain than for physical products. As such, mapping the real-world twin's state onto the digital twin's state often amounts to a profound measuring problem. Interpreting human-related measurements often requires extensive context information, primarily if few constraints govern the expected human behavior, like in many mobility systems.

We argue that HDTS can substantially help addressing problems of measuring and interpreting human behavior in open and complex environments. Designing, maintaining, and improving human-centric mobility services requires knowledge of many human-related attributes. Such knowledge does not have to be instantaneous or all-encompassing and should be restricted to the relevant information regarding the represented person. Still, a core tenet in Human Factors Engineering is "to ensure that something goes well, it is necessary to understand what goes on" (Hollnagel, 2021, p. 358). Achieving such an understanding requires integrating many aspects of travelers' experience during their journey, and what is relevant for an individual traveler may not always be evident from the outside. For mobility providers, travelers are only visible when entering their area of responsibility. For an individual traveler, however, the entire journey is essential, regardless of who is responsible for ensuring the journey goes well.

As such, representing the way travelers take through the various spaces of their journey poses similar challenges as representing physical products in the context of PLM. As a domain-specific application of HDTS, we argue that the concept of Digital Twins of Travelers (DTT) is a promising approach to represent humans as they journey through the traffic system and to integrate multiple data sources indicating their experiences during this time. Crucially, the approach provides a conceptual basis to represent the mobility-related context of the travelers' experiences, holding information about chosen routes or the journey trajectory concerning reached travel milestones (Rudolph et al., 2022). A twin system can help focus on a subset of human-related phenomena and the specific situations in which they occur, for example, to aid in understanding complex issues such as travel mode choice based on real-world data. In short, a DTT provides the framework to implement conceptualizations of mobility as travelers journey through time and space (Al Maghraoui et al., 2019).

Implementing the DTT concept requires (a) a clear theoretical and empirical basis for the construct of travel experience to know which human attributes can be represented and (b) use cases for applying the DTT concept to know what should be represented. Both aspects will be discussed in the following sections. Finally, open questions regarding data privacy and data ownership will be discussed.

2 Travel Experience

As an analogy to the construct of user experience that relates human affective experiences to technical system usage (Schrepp et al., 2017), travel experience refers to the collective subjective impressions and evaluations a traveler has in the context of a journey (Schiefelbusch, 2015). Travel experience is not restricted to using vehicles such as shuttles, trains, or cars but also addresses travel-relevant infrastructure such as stations, hubs, and technical systems such as ticket vending machines or apps (Barría et al., 2023; Bosch et al., 2023; Castro et al., 2020; Ihme et al., 2023). Further, relevant experiences may include the feeling of pleasantness when looking out of the window in a calm high-speed train, the frustration when learning that a bus has been canceled, or the discomfort caused by standing on a crowded platform.

Unfortunately, when using trains and other public transportation, many passengers regularly experience delays, missed connections, a lack of journey-relevant information, or long waiting times. If the negative experiences outweigh the positive experiences over a sufficient period, the likelihood of using individual modes of transportation, such as private cars, can rise considerably. However, we argue that properties of the public transport system, such as the state of the infrastructure or the number of delays, are only one factor influencing travel experiences and may not always be the most important one. As an affective-emotional state, journey-related experiences are not one-dimensional and do not perfectly correlate with any single measurement (Scherer, 2005).

Instead, travel experiences are heavily influenced by a person's goals, resources, and cognitive and physical state. Depending on those factors, a situation such as a train's delayed arrival at the next station could lead to various cognitive and emotional responses. Whereas some passengers may be indifferent because the station is their final destination, others could experience significant stress for fear of missing a connecting train with drastic consequences for the remainder of their journey. Particularly in case of missed connections, travelers with access to relevant information may be able to reschedule their journey quickly and consequently experience much less uncertainty than those relying on outside help to adapt their itinerary.

Ideally, the travelers‘ digital twin can represent a broad spectrum of emotional travel experiences such as frustration, uncertainty, anger, fear, discomfort, flow, or pleasantness. However, deriving such a wide variety of states from sensors such as fitness trackers, which can plausibly accessed during the travelers' journey, is a considerable challenge. Instead, a lean but robust approach mapping indicators of arousal to positive or negative valence could serve as a more practical first step (Russel, 1980). Recent work has employed this approach when assessing travel experience, recording valence or similar constructs based on one or two self-report items and arousal using physiological indicators (Barría et al., 2023; Bosch et al., 2023; Brandebusemeyer et al., 2022). Although this approach provides only a low resolution of the emotional spectrum, it operationalizes the construct traveler experience as an immediately applicable method that yields valuable results.

3 Use Cases for Digital Twins of Travelers

The first use case concerns exploring factors influencing passengers' travel experience. Representing attributes of specific persons with known itineraries allows a much better understanding of how they solve the task of traveling to their destination, react in case of unexpected events, and evaluate certain situations along their journey. Crucially, understanding factors influencing the travel experience can be improved iteratively by analyzing the data, formulating hypotheses based on insights gained, and testing those hypotheses by making predictions regarding novel situations. If specific context data is required to understand travel experience, it is possible to add such data post-hoc by querying relevant sources.

A second use case addresses the support of passengers directly during their journey. For example, by improving the digital twin's process model to represent the task-relevant goals of travelers during their journey, providing the real-world twin with relevant information to achieve their next goal becomes considerably more straightforward. Whereas the construct of travel experience addresses what a journey feels like, a DTT must also represent what needs to be done to complete the journey, i.e., hold a passenger's itinerary. In this view, the digital twin of a traveler is a construct for mapping, updating, and forecasting all relevant individual customer requests regarding their transportation. Specifically, itineraries can be modeled as the essential points or milestones of the service trajectory of the journey. Milestones include the journey's starting point and destination, the means of transportation on each leg of the journey, and, importantly, required transfers and associated waiting times between the legs of the journey (Engler et al., 2017). During the journey, the DTT updates arrival and departure times for the upcoming milestones depending on the actual traffic situation and adjusts the transfer times accordingly. Such a real-time itinerary would enable communication of a passenger's progress on their specific travel chain, allowing them to manage delays and disruptions of transport services with much better consideration of individual needs and preferences (Scheelhaase et al., 2023).

As a third use case, a DTT could be a valuable data source for better adjusting supplied services to the actual demands for transportation. Whereas travelers often know in advance the specific relations they will use, mobility service providers do not have access to that information. Thus, decisions regarding offering transport services must be based on forecasts, potentially causing providers to miss business opportunities for relations where an unknown demand exists. In local public transport, ticket options such as transit passes place few constrictions on how customers use existing transport services, making the capacity planning for specific routes challenging. Even if a service has been booked well in advance, it is not certain that the customer will use it. Obtaining insight into current and planned journeys and perhaps individual preferences may allow mobility service providers to provide more targeted services than today, even in day-to-day operations. For example, if passengers miss a connection due to a service failure, the impact will vary depending on the trip's purpose. Taking the aggregated impact of service failures into account could help allocate resources in a more targeted way.

Finally, the fourth use case concerns the predictions enabled by the DTT's process model. Reducing complex journeys to essential milestones discretizes otherwise continuous processes, making simulations of complex relations in the traffic system much more accessible. For example, the approach allows for predicting the effect of travelers' preferences on the usage of buses or trains. Preferences refer to variables such as the time travelers are willing to wait on average for a connection, the price they are willing to pay, or the maximum vehicle utilization they will tolerate. When considering changes to existing transport services, the effect of those changes can be simulated together with varying preference distributions. It may be challenging to validate the veracity of the simulation's outcome. However, we argue that even considering travel experience when planning transport services is a crucial first step to aligning offered services with existing demand.

4 Data Privacy and Data Ownership

In a nutshell, the concept of DTT suggests combining data indicating travelers' emotional state with relevant context information underpinned by a powerful abstraction of the traveling task. We have argued that such an approach offers many attractive features supporting a better understanding of human behavior and experiences in complex environments and solving mobility-related practical issues. However, we also believe that implementing the concept requires further discussions regarding data privacy and data ownership. To be useful, the digital twin must represent its real-world counterpart's highly sensitive personal data, such as physiological data, self-reports, timetables, and traveler trajectories. As described in the use cases, leveraging the DTT's full potential requires sharing parts of the collected data with third parties, like mobility service providers. As such, effective precautions to eliminate, minimize, and mitigate threats to data privacy are indispensable. On the other hand, the EU's General Data Protection Regulation (GDPR) already regulates many aspects of collecting and processing private data. Any implementation and operation of DTT would need to adhere to the GDPR and other data protection regulations.

In any case, we suggest thoroughly addressing data privacy and data ownership already on the architectural level. First, travelers using a digital twin must have complete control over the collected data, especially regarding sharing such data with third parties. Second, if users are unwilling to share some data, they need to be able to use the subset of the DTT's functionality, which is still available. Third, data must be anonymized or at least pseudonymized immediately. For example, aggregated data is likely sufficient if a mobility service provider is interested in how service failures impact traveler experience. Fourth, data ownership at each processing step must be clear. As such, roles and responsibilities ensuring compliance with data privacy regulations must be considered as part of the DTT design phase.

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