Defining Seamless Multimodal Transportation through Four Key Principles: A Systematic Approach

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Abstract

The concept of seamless mobility has emerged as a solution for addressing complex challenges of urban transportation problems. However, ambiguity surrounds the concept, with uncertainty about its core characteristics and how it can be effectively advanced. To address this gap, this study defines a set of core characteristics and schemes associated with seamless mobility and summarizes the initial findings of a wider systematic review totaling 2205 studies. Through a screening process based on four principle layers of seamless mobility, namely, infrastructure, transport modes, system management, and user interface, the studies are distilled to 91. The results show how each of them contributes to specific aspects of seamless mobility must be included in its definition. Moreover, the results highlight the influence of emerging technologies, such as Internet of Things and Automated Driving, on certain research schemes. This study provides initial insights into a clearer definition of seamlessness and its practical application.
Keywords: Multimodal transportation systems, seamless mobility, systematic review

1 Introduction

The concept of seamless mobility has emerged as a solution to address complex challenges of urban transportation problems. Seamless mobility refers to an integration of multiple transport modes to provide a smooth end-to-end connection (EC, 2011). Numerous efforts have been made steadily to improve seamlessness with respect to the quality, accessibility, and reliability of transport services for both passengers and freight.

Seamless mobility is a multifaceted concept that is associated with a number of factors and a multiplicity of definitions (Potter, 2010; Givoni & Banister, 2010). Various factors include public transport information, physical transport services, ticketing and fares, infrastructure provision, transport authorities, and land use planning policies (Preston, 2012). With respect to these factors, studies have been conducted in a wide variety of transportation-related areas. For example, Costa et al. (2016) proposed a solution for seamless mobility in terms of leveraging personal mobile devices in combination with collaborative exchange of transport information. Conticelli et al. (2021) assessed the performance of policy measures and physical configuration designs in interchange hubs to promote seamless mobility. Ceder (2021) considered seamless mobility as smooth transfers between transport modes, which the future direction of transportation research should aim for.

Although related studies have been implemented within their research scopes around the world, there is ambiguity surrounding the concept of seamlessness; it is uncertain what the core characteristics are and in which way they can be advanced. The terminology used without any order or structure not only weakens conceptual clarity but also risks blurring the literature for future research. Therefore, this study summarizes a systematic review to define a set of core characteristics and schemes of seamless mobility, so as not to lose depth in the pursuit of enhancing traffic operations. The systematic literature is organized into four categories of relevant research subjects that appear to each contribute to the wider definition of seamlessness.

Principles of Seamless Mobility

In this section, some key concepts related to seamlessness are introduced. According to Knupfer et al. (2018), mobility systems can be evaluated by five key indicators: availability, affordability, efficiency, convenience, and sustainability. As illustrated in Figure 1, these indicators represent the traveler's experience before, during, and after each trip. First, in the before-trip phase, users decide on travel routes by assessing candidate trip information. *Availability* refers to the variety of transport mode options available to users. Users might evaluate combinations of transport modes for their trips. Specifically, they consider which modes are available for their trips, how well the road infrastructure for each mode is structured, and how effectively the modes are connected to each other. In addition, users consider *Affordability* that represents the relative cost of the transport options available compared to the average income. They decide combinations of modes by comparing their value of time and travel costs. Second, in the during-trip phase, users see quickness and reliability as *Efficiency*. The transport modes with high speed and reliability in time are likely to be chosen for their trips. Furthermore, *Convenience*, or the quality of service, is important for the users to choose. Lastly, in the after-trip phase, users consider *Sustainability* by checking if the transport modes are safe and environmentally friendly to use again.

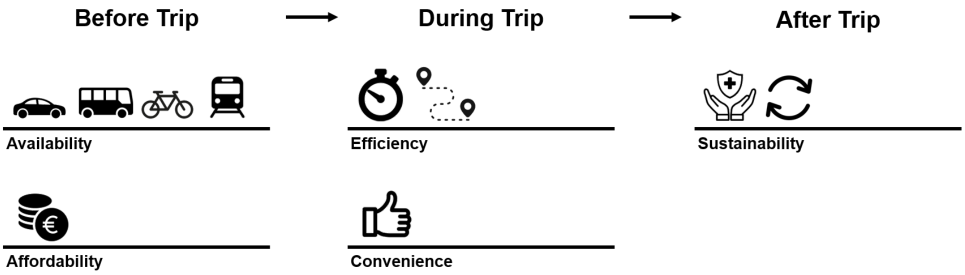

Figure 1: Indicators for mobility systems

Then, adopting these five indicators, Hannon et al. (2020) proposed four principle layers for seamless mobility. As shown in Figure 2, infrastructure in the first layer indicates the supply side of transportation that is responsible for the capacity of the network. It can be improved not only by adding physical installations but also by improving utilization with advanced technology. Above that, transport modes are operating on the road network as the second layer. Advancement of vehicle technologies and the adoption of new transport modes will enhance seamlessness. System management as the third layer coordinates the infrastructure and transport modes for traffic operations. The top layer is the user interface, which provides users with a convenient environment to utilize transportation systems. This framework is assessed against the analyzed literature, to verify its relevance towards a wider definition of seamlessness in transportation, as reported in the following.

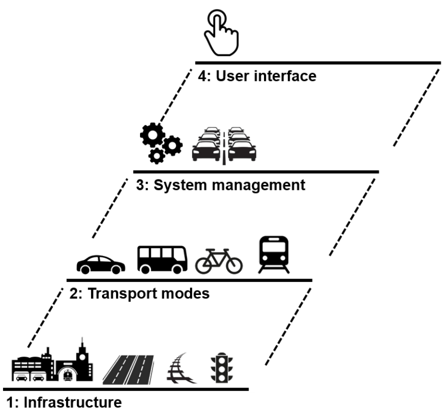

Figure 2: Four principle layers for seamless mobility

Objective of the Study

The term "seamless" has been used with a wide variety of concepts, resulting in an ambiguous and divergent consensus. Therefore, this study describes the steps being carried out to perform the systematic review, with the final aim of characterizing seamlessness for passenger mobility. This review synthesizes the available evidence and research studies using the scope of the four principle layers (Hannon et al., 2020). Through a rigorous and comprehensive search methodology, the core characteristics are identified that explore the research schemes of seamlessness. By critically analyzing the findings, this study provides insights into the definition of seamlessness.

2 Methodology

To conduct a systematic search and review of existing studies on seamless mobility, this study leverages the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). PRISMA is a comprehensive set of evidence-based items intended for use in reporting systematic reviews and meta-analyses. Specifically, the PRISMA guidelines aim to ensure adequate reporting of systematic reviews that evaluate the effects of interventions, although they have been utilized to report systematic reviews with other objectives. By providing a standardized set of reporting items, PRISMA facilitates complete and transparent reporting of systematic review research (Moher et al., 2009).
To establish the eligibility criteria for this systematic review, the Sample, Phenomenon of Interest, Design, Evaluation, and Research type criteria (SPIDER) framework was utilized. The SPIDER method was preferred due to its suitability in qualitative research and its ability to handle limited resources and time (Cooke et al., 2012; Methley et al., 2014). The SPIDER criteria for conducting this systematic review on seamless mobility are as follows:

- ***Sample***: The review included studies that investigated the effectiveness of seamlessness in improving traffic operations in multimodal transportation system, its current state, and potential future impact. The sample included studies from various countries, regions, transport services, transport technologies, and users.
- ***Phenomenon of Interest***: The review focused on seamless multimodal mobility and its key principles. The study period from 2008[1] to 2024 was considered to target the most up-to-date research on seamless mobility.
- ***Design***: The review included experimental, observational, simulation, and case studies on seamlessness.
- ***Evaluation***: The review evaluated the effectiveness of seamlessness in improving multimodal traffic operations, reducing congestion levels, and promoting smooth connectivity between transport modes. The impact of each of the four layers of seamlessness was also evaluated. The potential of seamless mobility to improve future traffic operations was examined.
- ***Research type***: The review covered all types of publications, including journal articles, conference papers, white papers, reports, and books from all over the world related to seamless mobility. The studies were selected based on predefined exclusion criteria.

To perform a comprehensive literature search, various databases were utilized, including Crossref, Google Scholar, PubMed, Scopus, Semantic Scholar, and Web of Science. Search terms include "seamless multimodal transport," "seamless intermodal transport," "integrated public transport system," "seamless multimodal mobility," "seamless transport," "seamless mobility," "seamless traffic," "seamless traffic management," "seamless transport connectivity," "seamless transportation system," "seamless MaaS (Mobility-as-a-Service)." Moreover, their variations were used to ensure a broad coverage of the studies, based on their relevance to the phenomenon of interest.

[1]Based on our review of the literature, limited studies address seamless mobility prior to 2008.

PRISMA Approach

Figure 3 represents the PRISMA approach to systematic review. First, the titles and abstracts of the retrieved literature were screened to determine whether they met the criteria of the SPIDER framework. Subsequently, the full texts were evaluated to assess their eligibility for inclusion in the systematic review. A total of 2,205 records were identified and extracted from the database search. Following the removal of duplicate records, the screening process resulted in 824 studies that underwent further screening to identify the studies that met the eligibility criteria as defined by the SPIDER framework. This resulted in a total of 124 studies that were then considered for full-text screening. After conducting the full-text screening, 31 articles were excluded according to the predefined exclusion criteria, i.e., publication prior to 2008, non-English language, or misalignment with the study's objectives and principles, leaving 91 records selected for the final systematic review. The final 91 records were then categorized according to the layers of seamless mobility (Hannon et al., 2020).

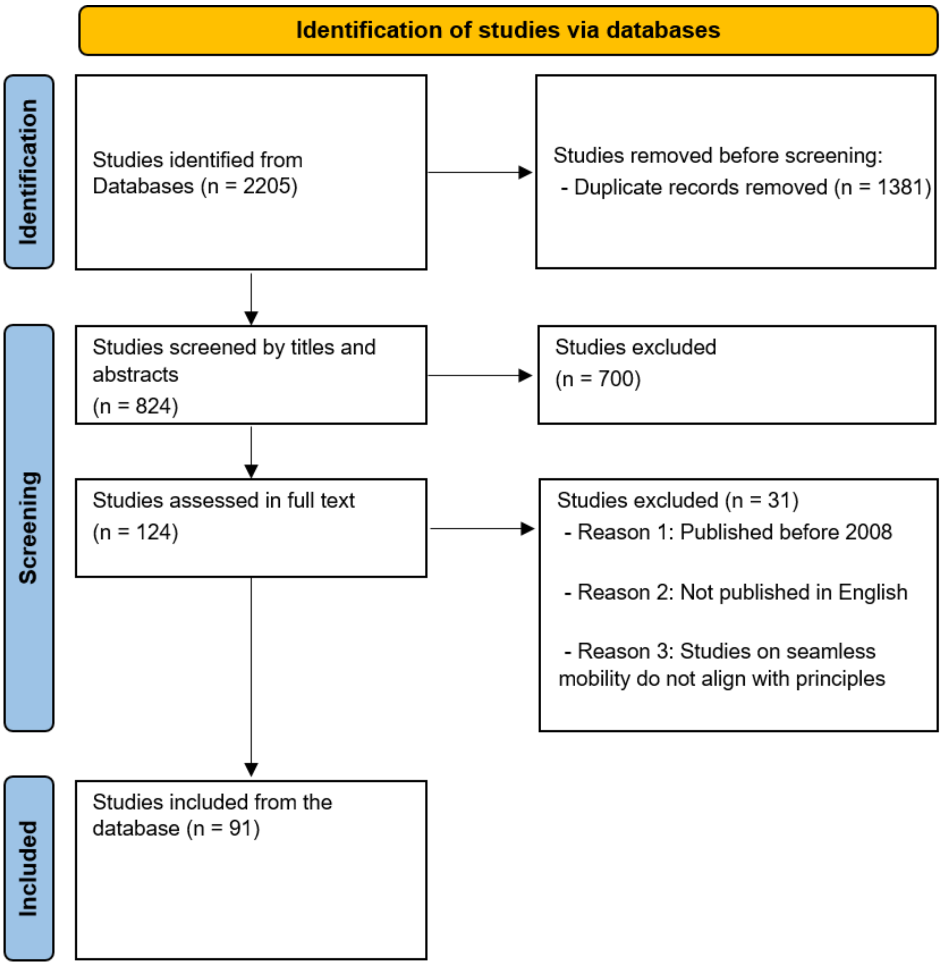

Figure 3: Flowchart for systematic review on seamless mobility using PRISMA guideline

3 Results and discussion

Results

This section presents the initial findings through the lenses of the identified four key principle layers, focusing on 91 studies that emphasize and characterize the concept of seamlessness. As depicted in Figure 4, the 91 selected studies are categorized into four layers: infrastructure (24 studies), transport modes (10 studies), system management (26 studies), and user interface (11 studies). Each layer is further divided into several research schemes, with key representative studies for each scheme described below.

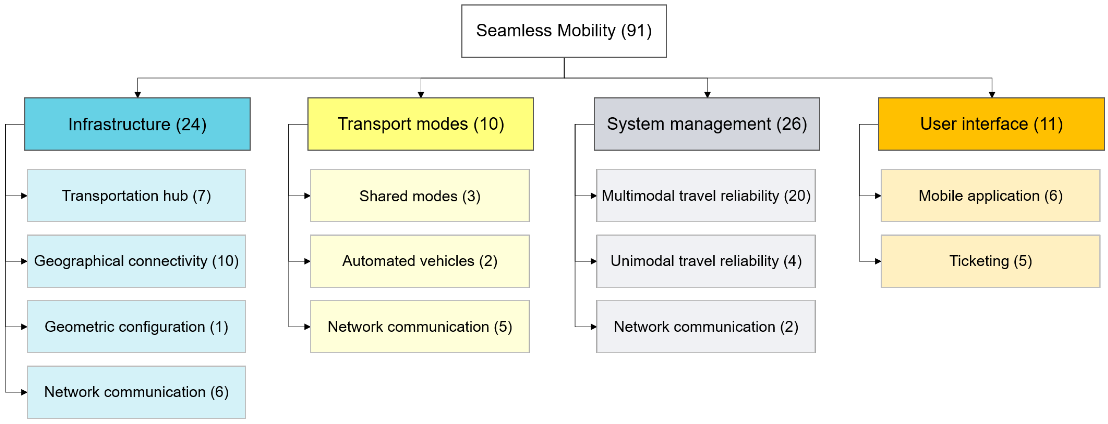

Figure 4: Research schemes of seamless mobility studies

Infrastructure is a critical supply-side component that manages transfers between transport modes or vehicle movements on roads. By applying the principles of seamless mobility, the infrastructure can benefit from a more sustainable and long-lasting approach to mobility. The traditional approach is to build more roads, bridges, rail lines, and other facilities, but doing so can be difficult and costly in dense, developed cities. Considering the limitations, recent developments focus on increasing the utilization of existing infrastructure within limited supply.

- ***Transportation hub*** provides a space while integrating and synchronizing various modes of transport, which facilitates decongestion, reduces travel time, provides a preferable transfer environment, and eventually provides seamless and sustainable mobility (Chauhan et al., 2023; Arnold et al., 2023). With limited resources and supply, the relevant studies minimize transfer walking distances, investigate passenger behavior, and identify the most efficient places for transportation hubs (Zeng et al., 2024).
- ***Geographical connectivity*** investigates whether major transport points are well connected with corridors, highways, or freeways as large-scale networks (Labi et al., 2019; Esztergár-Kiss et al., 2022). This leads to the development of smart and seamless corridors connecting industrial or logistics clusters by solid, safe, and secure infrastructures, real-time connectivity and information sharing, reduction of administrative burdens, and enhanced intelligent control for resilient and flexible service provisioning (Oonk, 2016).
- ***Geometric configuration*** is considered to properly control traffic flow by sensing traffic volumes and congestion (Meneguzzer et al., 2017). Dynamic lane control system is one example of alleviating traffic congestion (Pasha et al., 2024). For another, road design standards can also be managed using vehicle driving behaviors in specific road segments for seamless mobility (J.-Y. Lee et al., 2023).
- ***Network communication*** uses the Internet of Things (IoT) to improve the operational efficiency of road networks with specific purposes (Kiss et al., 2014; Musa et al., 2023). For example, a method for vehicle-to-infrastructure connection is suggested that detects emergency vehicles on the road, monitors traffic conditions, and automatically controls traffic signals to provide a clear path for emergency vehicles to reach their destination without stoppages (Joselin et al., 2024).

Transport modes consist of cars, buses, trams, metros, trains, bikes, scooters, and so on. In this context, seamless mobility is considered to improve traffic operations using metrics such as passenger kilometers, waiting time, transfer time, and total travel time. Relevant studies redesign product portfolios and business models with new alternative transport modes and emerging vehicle technologies, which can bridge gaps between existing transport modes by offering services, and can improve the modes' capabilities themselves, respectively.

- ***Shared modes*** gained interest with the rise of urban environmental issues and the shared economy, adopting emerging concepts such as ride-sharing, ride-hailing, and shared transit. Ride-hailing services complement mass transport by making the first and last-mile trips more convenient (Sunitiyoso et al., 2022). Shared mobility improves the urban environment and life quality as well as transportation system efficiency (E. Lee et al., 2020; Garus et al., 2024).

- ***Automated vehicles*** are expected to transform the future of intelligent transportation systems (Hasan et al., 2019). In particular, the vehicles with prompt reaction times improve traffic operations, consequently improving the capacities of the road network (Kesting et al., 2010; Papamichail et al., 2019; E. Lee et al., 2024). Moreover, automated transit systems, such as autonomous shuttles, offer a transformative mobility solution for city centers where narrow streets are not easily served by traditional transits, creating a sustainable, integrated, and seamless mobility (Bucchiarone et al., 2020).
- ***Network communication*** between transport modes and infrastructure has increasingly become an important technology to maintain high quality communication in the era of intelligent transportation systems (Vegni et al., 2011). As the speeds of transport vehicles increase, wireless network infrastructure in facilitating seamless handovers is critical for ensuring the safety, efficiency, and reliability of traffic infrastructure (Lim & Tuladhar, 2018).

System management refers to data and analytics such as real-time traffic information, vehicle routing, and traffic flow management. As different types of vehicles are operated on the road network, integrated collaborative systems using sensor applications and optimization models are introduced for the efficient utilization of each business model or their connections.

- ***Multimodal travel reliability*** in the dynamic urban lifestyle encourages users to choose multiple transportation modes, ensuring seamless and convenient trips with high transfer quality (Allard & Moura, 2018; Ceder, 2021). For example, Mobility-as-a-Service (MaaS) integrates a wide range of mobility services, such as public transportation, bike-sharing, and carpooling, to provide a more convenient and more sustainable solution (Mitropoulos et al., 2023).
- ***Unimodal travel reliability*** considers the optimization and scheduling of a single mode's route can improve overall traffic operations in collaboration with other modes (Baykasoğlu et al., 2019; K. Lee et al., 2022). In addition, traffic management strategies that target specific road segments regardless of vehicle type include pricing, perimeter traffic signal control, ramp metering, and vehicle routing (Tirachini & Hensher, 2012).
- ***Network communication*** focuses mainly on the reliability of real-time traffic information that users can refer to for their route choice behaviors, achieving more seamless mobility and a higher quality of service (Gerla & Kleinrock, 2011). For example, drone-based real-time traffic monitoring systems bridge connectivity gaps of traditional communication infrastructure, specifically when incidents occur in unobservable road segments (Ahmad et al., 2024). Another example is Traffic Management-as-a-Service (TMaaS) that performs a two-directional communication between traffic system operators and users to send and receive traffic information back to the system for a more sophisticated system (Grandsart et al., 2020).

User interface establishes easy-to-use platforms to provide a convenient user experience. This interface brings transportation business models together as part of a future transport ecosystem. It enables users to fully benefit from the offered transport systems, and they decide on choices of infrastructure, transport modes, and system management.

- ***Mobile application*** provides users with trip options and suggests optimal routes that efficiently integrate the different modes for their trips (Ferreira et al., 2023). This mobile application serves as a journey planner to achieve the main goal being the provision of a holistic urban mobility solution through a single interface (Georgakis et al., 2020).
- ***Ticketing*** represents an integrated ticketing system for multimodal payments. Each transport mode may require its own payment method, which requires users to establish multiple payment accounts. The integration of payments is part of bundled mobility services, providing users access to many mobility options (Ferreira et al., 2023). It allows users to put minimal effort into their plans and make their travel experiences seamless (Dinning & Weisenberger, 2017; Urban et al., 2017).

Research Schemes	Main Solutions	Main Criteria for Seamlessness
Infrastructure		
Transportation hub	Locating hub facilities	Reduced transfer distance
Geographical connectivity	Assigning pivotal points	Reduced travel time
Geometric configuration	Designing roads	Increased traffic speed
Network communication	Monitoring traffic	Improved traffic speed & reliability
Transport modes		
Shared modes	Improving operational efficiency	Improved accessibility
Automated vehicles	Improving driving ability	Improved traffic speed & accessibility
Network communication	Monitoring individual vehicles	Improved reliability
System management		
Multimodal travel reliability	Improving multimodal connections	Reduced transfer time
Unimodal travel reliability	Improving each mode's operations	Increased traffic speed
Network communication	Monitoring traffic information	Improved traffic speed & reliability
User interface		
Mobile application	Finding multimodal route options	Improved route-finding convenience
Ticketing	Ticketing multiple mode options	Improved payment convenience

Table 1: Research schemes and main criteria for seamlessness

In the context of the four principle layers outlined in Table 1, seamlessness in traffic operations has been defined using criteria such as "transfer distance," "travel time," "traffic speed," "accessibility," "reliability," "route-finding convenience," and "payment convenience." These definitions provide valuable insights into key focus areas for traffic-related research aimed at improving seamless mobility. Moreover, these can serve as a reference for evaluating whether seamless mobility studies are progressing in the right direction.

Discussion

Results indicate that the existing literature regarding seamless mobility can be primarily categorized within the infrastructure and system management research schemes (approx. 25 studies in each versus approx. 10 studies in each of transport modes and user interface schemes). Reliability while traveling within multimodal environments dominates the share of studies across all schemes. This is an intuitively expected finding, since reliability in services is a commonly met performance metric for various transport systems and a common objective for optimizing transport services. Although advances in technology allow more user-friendly environments for reaching transport services nowadays (e.g., mobile phone apps for ticketing purposes or MaaS platforms), this scheme does not seem to receive proper attention from researchers in the area of seamless mobility compared to more well-established schemes (e.g., infrastructure). Emerging vehicular technologies for seamless mobility appear to be a field of research that could be further expanded in the future. Although recent studies highlight the critical role that automated vehicles can play in the mobility ecosystem, only two studies have related this technology with seamless mobility.
The quality of core characteristics related to the principles of mobility systems will be improved by emerging technologies, such as the IoT and autonomy (Hannon et al., 2020). The spread of IoT technology to infrastructure and transport modes enabled new types of trips, such as ride-sharing and e-hailing. It also has made existing infrastructure and modes more efficient, reducing maintenance costs. Automated technology has already been adopted for various real-world activities, such as driverless shuttles in a limited area and automated user-transit services.

4 Conclusions

The novelty and not-well-defined natures of seamless mobility make it challenging to ascertain what seamlessness is, its implications, and how to advance it. This study distills a set of core characteristics of seamless mobility by reporting initial insights from wider a systematic review of a total of 2,205 studies. The results present an overview of the four principle layers (i.e. infrastructure, transport modes, system management, and user interface) and how the state-of-the-art relates them to a definition of seamlessness. Indeed, the categorization of a wide range of research schemes in each layer provides how the terminology "seamlessness" has been used in the field of transportation engineering. Moreover, some schemes appear to be affected by emerging technologies such as IoT, autonomy, and electrification. By clarifying the characterization and applications of seamless mobility, this study provides a foundation for future research and practical advancements in creating more integrated and efficient transportation systems.

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