International Journal of Computational and Experimental Science and ENgineering (IJCESEN)

Vol. 11-No.3 (2025) pp. 4580-4586
http://www.ijcesen.com

ISSN: 2149-9144

Research Article

Evidence Triangulation for Public Transport Innovation: A Mixed-Methods Study on Real- Time Information Systems

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Article Info:

DOI: 10.22399/ijcesen.3071
Received : 22 April 2025
Accepted : 25 June 2025

Keywords

Public transport,
Digital systems,
User satisfaction,
Safety, accessibility,
Mixed methods

Abstract:

This study examines the effects of real-time public transport information systems using a mixed-methods approach. Combining 14 expert interviews and over 10,000 user surveys, it applies evidence triangulation to assess how digital innovation influences service perception and policy relevance. Experts rate real-time data as a high-impact governance tool for enhancing trust, accessibility, and planning reliability—especially for users with limited mobility or orientation. Quantitative analysis confirms this view: access to digital information is significantly associated with higher user satisfaction, particularly among occasional or unfamiliar riders. The study highlights transparency, predictability, and perceived control as key acceptance factors. It proposes a transferable framework for evaluating innovations in transport through the integration of expert judgment and user feedback. Findings underscore the importance of user-centered indicators and call for adaptive monitoring tools to guide investment in digital infrastructure. Real-time systems emerge as a critical component of inclusive and responsive transport strategies

1. Introduction

1.1 Background and problem

Advancing climate change and the urgent need to reduce transport-related emissions make the mobility transition one of the key challenges of our time. The transport sector accounts for around 20% of total emissions and therefore requires far-reaching technological, political, and social transformations. In this context, local public transport (LPT) has a key role to play: as a low-emission mode of transport, it can make a significant contribution to reducing private transport while also relieving pressure on urban and suburban living spaces. Political initiatives such as the German Climate Protection Act and the Europe-wide "Fit for 55" package underscore the need for a structural reorientation of the mobility system. Initial measures such as the €9 ticket have had a short-term impact on mobility behavior, but have also highlighted the structural limitations of the existing system. A sustainable transport transition therefore requires not only affordable prices, but above all innovative, user-centered, and long-term viable solutions. At the same time, technological innovations are fundamentally changing mobility behavior. Electric mobility, autonomous driving, digital platforms, and integrated mobility services in the sense of Mobility-as-a-Service (MaaS) are creating new possibilities for transport organization. However, these developments are accompanied by considerable demands on infrastructure, operational processes, and user acceptance. The COVID-19 pandemic has further accelerated these dynamics by establishing digital working models and increasing demand for flexible, integrated mobility solutions. In the midst of these transformation processes, the question arises as to which innovations have the potential to make public transport fit for the future – and how their impact on user satisfaction and demand can be empirically measured. The aim of this study is therefore to systematically evaluate disruptive technologies and mobility concepts in terms of their opportunities and risks and, on this basis, to formulate evidence-based recommendations for action for a sustainable, user-oriented transport policy.

1.2 Field of research and system boundaries

The subject of the study is local public transport in a densely populated urban area with a high density of commuters, complex infrastructure, and a polycentric settlement structure—analyzed in the context of a regional transport association. The study not only focuses on traditional scheduled transport, but also takes into account the extended mobility ecosystem, which includes sharing services, on-demand services, and multimodal platforms. To clearly structure the scope of the study, an analytical distinction is made between three transport segments:

• Private transport: This includes private means of transport such as cars, bicycles, and walking. Although this is not the focus of the analysis, its interaction with public transport – for example, in the context of intermodal platforms or autonomous vehicles – is relevant for the consideration of the modal split.

• Privately organized non-public transport: This includes commercial services such as ride sharing and tourist transport. These systems are increasingly operating in the same space as public transport and, depending on their level of integration, can be both competitive and complementary.

• Public transport: The focus here is on scheduled services such as buses, suburban railways, and trams. Public transport is undergoing change – from electrification and digital real-time systems to automated forms of operation. The question of how user- centered service design, pricing structures, and technological innovations influence acceptance and demand is particularly relevant.

The theoretical framework includes the choice rider theory, the technology acceptance model (TAM), and behavioral pricing theories, which together provide a comprehensive understanding of behavioral and structural factors influencing mobility decisions.

1.3 Relevance and research gap

Despite political objectives and technological advances, the share of public transport in the modal split is stagnating in many European regions. At the same time, the number of available mobility services is increasing without their systematic integration into a sustainable overall system. Empirical findings on the impact of disruptive innovations on user satisfaction are fragmentary to date—in particular, there is a lack of integrative analyses that combine technological potential and social science user data. Furthermore, it is unclear how different user groups react to technological innovations and what role social, economic, or geographical factors play in this. This study addresses this research gap with a mixed-methods approach that combines qualitative expert assessments with quantitative user data. This methodological approach makes it possible to compare the innovation potential of disruptive technologies with actual user acceptance and to derive practical recommendations for transport companies, policy makers, and planning actors. The next chapter systematically reviews the theoretical foundations and the current state of research in order to anchor the empirical analysis in a methodologically and substantively sound manner.

2. Conceptual Framework

This study pursues a methodological and conceptual approach to the systematic evaluation of user-centered innovations in local public transport (LPT). The aim is to demonstrate the methodological potential of a mixed-methods design that triangulates qualitative expert judgments with quantitative user data in order to map evidence-based causal relationships between technological innovations and user perceptions. The methodological approach is transferable to various innovation measures and is demonstrated in this article using the example of real-time traffic information and navigation.

2.1 Methodological evaluation of innovations in the mobility context

Innovation in public transport does not only refer to the technical introduction of new products or systems, but also encompasses their operational, organizational, and perception-related integration into everyday mobility. Relevant developments such as digital information systems, flexible service offerings, or new platform technologies only have an impact if they appear understandable, accessible, and useful from the user's perspective. In order to capture these conditions methodically, this study uses a two-stage approach:

1. Expert-based assessment: Evaluation of the innovation potential (e.g., effectiveness, feasibility, social relevance) through semi-structured interviews with experts from planning, operations, science, and administration.
2. User-centered analysis: Quantitative examination of the impact of selected innovation features on overall perceived satisfaction with public transport based on standardized user interviews.

The methodological goal is to integrate these two perspectives in order to reveal not only technical and functional effects, but also social-psychological and behavioral effects.

2.2 Theoretical framework

To structure and interpret the results, an integrative set of theories is used that takes into account key psychological and behavioral economic factors influencing technology acceptance and mobility behavior:

• Technology Acceptance Model (TAM) [2]: This model serves as a basis for explaining individual acceptance of new technologies. It emphasizes the role of perceived usefulness (PU) and perceived ease of use (PEOU) as predictors of actual use. In the case study of real-time information, for example, it can be examined whether this is perceived as useful (PU) and easily accessible (PEOU) – and to what extent it influences satisfaction and use.

• Theory of Planned Behavior (TPB) [1]: This theory broadens the view to include subjective norms and perceived control over behavior. Perceived control over behavior is a key acceptance factor, especially for digital services (e.g., routing apps).

• Behavioral Pricing Theory: This complements the analysis with aspects of price perception, particularly with regard to transparency and fairness – factors that also become relevant in real-time systems, for example when waiting times are reduced or alternative routes are suggested.

• PESTEL approach: Political, economic, social, technological, environmental, and legal conditions structure the embedding of innovations. Technical maturity, regulatory hurdles, and data protection concerns are particularly important for digital information systems.

Together, these theoretical perspectives form the conceptual foundation for the operationalized analysis of innovation impact and user perception.

2.3 Target variables and evaluation logic

Instead of a comprehensive innovation assessment, this study focuses specifically on methodological evaluation criteria. Three central dimensions are defined as target variables for the analysis:

• Impact assessment (qualitative): Experts evaluate the potential impact of the innovation on operational efficiency, user-friendliness, environmental impact, and social acceptance.

• User satisfaction (quantitative): Measured using a standardized overall satisfaction scale (Customer Satisfaction Index) to statistically test correlations between innovation experience and user ratings.

•Integration capability: As an overarching criterion, we examine whether the qualitative assessment is confirmed or contrasted by the quantitative user perspective. This allows conclusions to be drawn about gaps between technical innovation and practical effectiveness in everyday life.

The innovation real-time traffic information and navigation serves as an exemplary case study because it has both high expert ratings and a strong user impact, making it particularly suitable for validating the methodological integration approach.

3. Study Area and Scope

This study focuses on the methodological testing of an integrated analysis approach for evaluating user-centered innovations in local public transport (LPT). A densely populated urban area in Central Europe serves as an exemplary field of investigation. For reasons of anonymity, the specific region remains unnamed, but it has typical characteristics that are common to many European metropolitan areas: high commuter flows, a polycentric settlement structure, multimodal transport systems, and increasing pressure to innovate in the wake of climate policy transformations. The analysis does not focus on the overall system, but rather on the application and testing of a mixed-methods approach to evaluating specific innovation measures. Real-time traffic information and navigation was selected as a case study—a digital service that is highly relevant for passenger information, route planning, and subjective feelings of safety. This example allows us to demonstrate how qualitative expert assessments and quantitative user evaluations can be triangulated to derive well-founded statements about the effectiveness and acceptance of an innovation. The study focuses exclusively on public transport services in the narrower sense, in particular on fixed-route systems (e.g., buses, trams, suburban rail) and their digital extensions (e.g., real-time apps, multimodal platforms). Two other transport segments are explicitly excluded:

• Individual transport (e.g., private cars, bicycles, walking) is only considered where it interacts systemically with public transport (e.g., in intermodal information systems).

• Commercial mobility services outside public transport (e.g., ride hailing, tourist shuttle services) are not systematically analyzed, as their nature is shaped by other regulatory and market-related dynamics

The aim is not to conduct a comprehensive comparison of innovations, but rather to demonstrate the methodological compatibility of combined survey methods using examples. The selected study region thus serves as a methodological test field in which the contextual conditions for digital information services can be realistically mapped—for example, in terms of infrastructure, user diversity, or service density. In this way, the study contributes to the further development of evidence-based evaluation methods for user-centered innovation strategies in public transport.

4. Methods

An explanatory mixed-methods design was implemented to empirically investigate the user-centered effects of digital innovations in local public transport. This combines qualitative expert assessments with quantitative user analyses in the form of a methodological triangulation in the sense of evidence-based innovation evaluation. This article presents a selected methodological aspect from a more comprehensive research project and focuses on the application field of real- time traffic information and navigation as a case study of methodological innovation.

4.1 Qualitative part: Expert-based innovation assessment

In the qualitative research part, central dimensions of innovation assessment – including probability of entry, system impact, social connectivity, and implementation barriers – were recorded on the basis of 14 semi-structured expert interviews. The experts interviewed came from transport companies, city administrations, technology companies, and research institutions. The selection was theory-driven and purposive in order to ensure the broadest possible range of institutional and regional perspectives. The data was evaluated using qualitative content analysis according to Mayring (2015) and supplemented with a deductive-inductive category system. In addition, a standardized evaluation grid was used, in which the experts could evaluate selected individual innovations according to comparable impact criteria. The resulting opportunity-risk matrix enabled a prioritized classification. This article focuses on an in-depth examination of the innovation "real-time traffic information and navigation," which was consistently rated as systemically relevant, feasible, and user-centered.

4.2 Quantitative section: User-centered impact analysis

A quantitative secondary data analysis was conducted to validate and contextualize the qualitative findings. The data was based on a scientifically weighted longitudinal data set of over 10,000 standardized user interviews collected as part of a continuous mobility survey between 2019 and 2023. The selection of the analysis variables was based on recognized models of behavioral and acceptance research, in particular the Technology Acceptance Model (TAM) [2], the Theory of Planned Behavior (TPB) [1], and the Behavioral Pricing Theory [4]. The focus was on explaining general user satisfaction, operationalized as a latent overall rating on a seven-point interval scale. The independent variables included both sociodemographic (e.g., age, education) and usage-related characteristics (e.g., ticket type, frequency of use, subjective sense of security, digital access to information). The following statistical methods were used:

- descriptive analysis for feature distribution and sample testing,
- t-tests and one-factor ANOVA to test group-specific differences,
- Pearson and Spearman correlations for bivariate relationships,
- multiple linear regression analysis to estimate significant predictors

All statistical prerequisites (normal distribution, homoscedasticity, multicollinearity, outlier sensitivity) were systematically checked. In the event of violations, robust methods were used (e.g., Welch ANOVA, regression models with HC3-corrected standard errors).

4.3 Data sources and methodological innovation through triangulation

The qualitative data set consisted of fully transcribed interviews that were coded using MAXQDA software. The quantitative data set was adjusted with design and post-stratification weights and methodologically validated. The integration of both data sources was carried out in the sense of a methodological triangulation according to Flick (2011): The aim was to systematically relate complementary knowledge – qualitative expert knowledge and quantitative user feedback – to each other. This combination makes it possible to ensure both the internal validity of individual findings and their contextualization in the usage situation. In the specific case of the innovation "real-time traffic information and navigation," this approach provides a multiperspective evidence base from which well-founded statements on impact potential, acceptance factors, and implications for action can be derived. The methodological design thus not only contributes to innovation research in public transport in terms of content, but also provides a transferable methodological approach for data-informed mobility strategies.

5. Results: Evidence-based evaluation of real-time traffic information and navigation

Within the mixed-methods design of this study, the innovation real-time traffic information and navigation was selected as an example to demonstrate the methodological interaction of qualitative and quantitative data collection for the

evaluation of user-centered public transport innovations. The selection of this innovation is based on its outstanding evaluation in the qualitative research part and its empirically verifiable relevance for user satisfaction in the quantitative analysis.

5.1 Qualitative assessment: system impact and implementation potential

In 6 of the 14 expert interviews conducted, real-time traffic information and navigation was named as one of the three innovations to be considered a priority. The innovation was consistently rated as highly effective in terms of operational efficiency, user-friendliness, and perception of service. Particular emphasis was placed on:

• increased transparency through reliable timetable information and delay notifications,
• improved planning of intermodal travel chains,
• and the potential increase in subjective safety through reliable real-time information.

The standardized evaluation of this innovation in the opportunity-risk grid resulted in the highest aggregate score of all 30 individual measures examined (107 points), with both the probability of occurrence and the potential impact being rated consistently high. Experts placed the innovation at the interface between digital transformation, operational optimization, and user empowerment strategy.

5.2 Quantitative validation: influence on user satisfaction

The quantitative analysis confirmed the high relevance of real-time information as a predictor of user satisfaction. The indicator "access to digital passenger information" showed a significant positive correlation with overall satisfaction ($r = 0.26$, $p < .001$). In multiple linear regression (adjusted $R^2 = 0.247$), this factor proved to be the third strongest significant individual predictor ($\beta = 0.18$, $p < .001$) after subjective sense of safety and frequency of use. Subgroup analyses also showed that passengers with little local knowledge, mobility restrictions, or no regular usage experience benefit disproportionately from real-time navigation systems. This supports the qualitative assessment that digital orientation aids act as a barrier- breaking component and play a decisive role in inclusion in public transport.

5.3 Integrative interpretation

The results of the qualitative and quantitative analyses show a high degree of consistency in terms of the impact and user relevance of real-time traffic information. The innovation addresses key factors influencing the perceived quality of the service, increases trust in the system, and supports subjective control over the mobility chain—three dimensions that have been identified in the literature as crucial for the acceptance of public transport (see [2]; [1]; [6]). The exemplary evaluation of this innovation demonstrates the methodological compatibility between expert-led assessment and user-based evidence and highlights the importance of real-time data as an interface between system logic and individual mobility decisions. The findings suggest that the implementation of such digital information systems is an evidence-based priority in the further development of public transport systems – especially from the perspective of sustainable, inclusive, and user-oriented transport policy.

6. Discussion

The case study analysis of the innovation "real-time traffic information and navigation" impressively demonstrates how integrated, evidence-based data collection can contribute to the evaluation of user-centered innovations in public transport. By systematically combining qualitative expert assessments with quantitative user feedback, a methodologically innovative approach is realized that places the governance of mobility innovations on a robust empirical basis (evidence triangulation for innovation governance).

6.1 Policy implications: Real-time information as a strategic lever

The results of the study show that real-time information systems as technological interventions not only enable operational improvements, but also trigger subjective effects on user experience, trust, and satisfaction. This makes them a strategic lever for evidence-based transport policy, especially with regard to reliability, predictability, and subjective control in everyday mobility. Politically particularly relevant is the potential of this innovation to reduce perceived uncertainty – a factor that has been empirically identified as a key determinant of satisfaction with public transport. The associated effect on modal choice and inclusion is particularly evident among groups with limited mobility, in peripheral regions, or among users with little local knowledge. International experience – for example in Helsinki or Vienna – confirms that real-time information systems are particularly effective where they have been implemented in an integrative, barrier-free, and interoperable manner (see [7]; [8]). The innovation thus not only contributes to service quality, but also addresses transport policy

objectives such as demand shifting, access equity, and climate protection. However, its effectiveness is contingent on governance structures, data protection standards, and technical interoperability being designed synergistically.

6.2 Methodological innovation: role of triangulated data collection

A central feature of the study is the methodological triangulation of qualitative-strategic and quantitative-empirical perspectives. This methodological innovation enables not only the evaluation of technical and operational functions, but also, and in particular, their subjective impact from the user's point of view – an aspect that is often insufficiently reflected in traditional service planning. The dual perspective allows both system effects and experience- based user needs to be identified in an evidence-based manner. It also shows that the social value of an innovation does not result from its technological complexity, but from its perceived usability and suitability for everyday use. This methodological approach can serve as a model for future studies on innovation assessment in the mobility sector, especially where social, technical, and regulatory factors interact simultaneously.

6.3 Limitations and transfer boundaries

The results of this exemplary analysis are subject to limited generalizability. The quantitative component is based on data from an urban European area with high digital penetration, which limits its transferability to less developed infrastructure contexts. Similarly, the qualitative part is exploratory in nature and does not provide a complete picture of the stakeholder landscape – perspectives that are technologically distant, marginalized, or not transport-related are potentially underrepresented. In addition, the study focuses on effects that can be observed at present, without being able to fully capture long-term behavioral changes or structural system transformations. There is a need for further research in the area of dynamic, longitudinal designs – for example, in the form of panel studies or impact monitoring in the context of specific implementation projects. Nevertheless, the methodological approach chosen here proves to be a valid model for evidence-based innovation assessment – transferable to other regions with comparable infrastructure, but also to other fields of innovation such as automated mobility, dynamic routing, or barrier-free platform integration. The work thus contributes to transdisciplinary mobility research that combines empirical foundations, political controllability, and user acceptance in an integrative analysis model.

7. Conclusion

This study examined the impact of the digital innovation real-time traffic information and navigation on user satisfaction and its significance for evidence-based control in public transport. The focus was on a methodologically innovative research approach that triangulates qualitative expert assessments and quantitative user judgments (evidence triangulation for innovation governance). The aim was not to describe technical functions, but to empirically capture subjectively perceived effects and strategic controllability from the perspective of users and stakeholders.

7.1 Key findings

The study shows that real-time traffic information, as a digital interface between the transport system and the user experience, makes a significant contribution to increasing the subjectively perceived reliability, transparency, and control in public transport. Experts classified these systems as high-priority governance instruments, particularly with regard to trust, social inclusion, and flexibility in dynamic networks. The quantitative analysis confirmed this assessment by identifying significant correlations between information availability and overall passenger satisfaction. This provides empirical evidence for the thesis that digital information systems not only generate technical efficiency gains but also behavior-relevant quality experiences – an aspect that has been neglected in many service planning processes to date

7.2Digital evidence as a planning resource

The results allow concrete implications to be drawn for the management of sustainable mobility: Real-time information systems should be understood as socially effective infrastructures, whose evaluation and promotion must be based on indicator-supported monitoring systems. Instead of purely operational KPIs, subjective indicators such as perceived control, information availability, and digital comprehensibility are coming to the fore. In political and strategic terms, this results in an expanded evaluation framework for digital investments that reflects not only technical feasibility but also everyday effectiveness, social accessibility, and trust. The establishment of user-centered feedback systems and dynamic evaluation tools appears to be central to this.

7.3 Research perspective: transferability and further development

The exemplary analysis not only demonstrates the strategic value of digital real-time systems in public transport, but also highlights the scientific potential of triangulated method designs. Three key areas of future research have emerged:

- Transferability to other contexts: The methodological approach is suitable for application in other fields of innovation (e.g., automated mobility, barrier-free platform design) and in different types of spaces, taking into account digital infrastructure levels and usage cultures.
- International comparative studies: Systematic links should be established with international studies (e.g., [7]; [9]) in order to identify cross-national success factors for digital innovations in multimodal systems.
- Model-based control: Linking qualitative acceptance dimensions with agent-based simulation models and behavioral planning approaches opens up new perspectives for dynamic control instruments in the mobility sector.

7.4 Conclusion

Digital real-time information does not work through its technical sophistication, but through trust, orientation, and social connectivity. Its impact unfolds at the interface between technical infrastructure, subjective experience, and political control. This study provides a methodologically validated example of how evidence-based innovation assessment can be designed in the mobility sector—as a basis for a sustainable, data-informed, and socially equitable mobility policy.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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