International Journal of Transport Development and Integration
Vol. 9, No. 2, June, 2025, pp. 227-237
Journal homepage: http://iieta.org/journals/ijtdi

A Review of Modeling Approaches in Multi-Modal Transportation Systems: Optimization, Travel Behaviour, and Network Resilience

Mohd Azizul Ladin[1*], Jazmina Bazla Jun Iskandar[1], Almando Abbil[1], Nazaruddin Abdul Taha[1], Rusdi Rusli[2], Muhamad Razuhanafi Mat Yazid[3], Hussin A. M Yahia[4], Al Sharif Ramzi[1]

[1] Faculty of Engineering, Universiti Malaysia Sabah, Kota Kinabalu 88400, Sabah, Malaysia
[2] Faculty of Civil Engineering, Universiti Teknologi MARA, Shah Alam 40450, Selangor, Malaysia
[3] Department of Civil Engineering, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia
[4] Civil Engineering Department, Middle East College, Knowledge Oasis Muscat, Al Rusayl 124, Sultanate of Oman

Corresponding Author Email: azizul@ums.edu.my

Copyright: ©2025 The authors. This article is published by IIETA and is licensed under the CC BY 4.0 license (http://creativecommons.org/licenses/by/4.0/).

https://doi.org/10.18280/ijtdi.090202

Received: 8 April 2025
Revised: 22 May 2025
Accepted: 3 June 2025
Available online: 30 June 2025

Keywords:
multimodal transportation system, travel behaviour analysis, optimization models, network resilience, agent-based simulation, sustainable urban mobility

ABSTRACT

Multi-modal transportation systems (MMTS) play a critical role in enhancing urban mobility by integrating multiple transport modes to improve efficiency and accessibility. This paper presents a comprehensive review of modelling approaches in MMTS, focusing on optimization techniques, travel behaviour analysis, and network resilience. The study synthesizes a range of methods, including agent-based models, equilibrium approaches, and data-driven simulations, aimed at improving system efficiency, adaptability, and user satisfaction. While significant strengths include real-world data integration and dynamic performance modelling, a thematic analysis reveals recurring limitations across studies, such as model assumptions, data limitations, limited behavioural realism, narrow scope, and high computational complexity. These weaknesses constrain the scalability and applicability of current MMTS models. The review emphasizes the need for frameworks that integrate real-time analytics, support diverse travel behaviours, and incorporate emerging trends like Mobility-as-a-Service (MaaS) and micromobility. It concludes by recommending that future research prioritize cross-regional validation, computational scalability, and dynamic system responsiveness to ensure MMTS can meet evolving urban transport demands. This synthesis serves as a critical reference for researchers, planners, and policymakers aiming to develop resilient and efficient multimodal transit networks.

1. INTRODUCTION

Urban mobility is becoming increasingly complex, requiring transportation systems that are efficient, resilient, and adaptable to diverse commuter needs. Multi-modal transportation systems (MMTS) integrate multiple transport modes—such as public transit, ridesharing, cycling, and walking—to provide seamless mobility and improve accessibility [1, 2]. Recent studies highlight that urban accessibility is influenced by connectivity, intelligibility, and proximity to public transport services, which directly impact pedestrian mobility and the effectiveness of MMTS [3]. A well-designed MMTS enhances travel efficiency, reduces congestion, and promotes sustainability, ensuring that urban transportation networks can accommodate growing populations and evolving mobility patterns [4].

A case study was done in Egypt, and results showed that the implementation of effective multimodal transportation had improved the level of service (LOS), increased accessibility between cities, and reduced traffic congestion [5]. One of the strategies to be implemented is creating a strong central core consisting of transit hubs, government buildings, town squares, surrounding non-residential development, land use divisions, and high-density residential as shown in Figure 1 [6].

Hong Kong has also implemented MMT by developing an extensive transportation network with buses that are widely available throughout the city. At the end of 2022, there were 522 bus-bus interchange schemes that had been promoted to increase the efficiency of the buses and had been improved with air-conditioning for the convenience of the users [7]. By connecting different modes seamlessly, MMTS enables smooth transitions across transport types, reducing travel time and increasing convenience for commuters. Cities worldwide look to this model to improve mobility as the number of private vehicles continues to rise [8, 9].

However, many cities face challenges in implementing optimized MMTS models that balance operational efficiency, travel behaviour, and network resilience. Besides that, the rise in private vehicle ownership and increasing urbanization have led to traffic congestion, longer commute times, and higher carbon emissions, straining existing transport networks [10]. Traditional single-mode transport models, which primarily focus on either private cars or standalone public transit services, are becoming inadequate in meeting modern mobility demands [11]. To overcome these challenges, multi-modal transport models must incorporate robust optimization techniques, travel behaviour analysis, and resilience strategies to enhance system efficiency and adaptability.

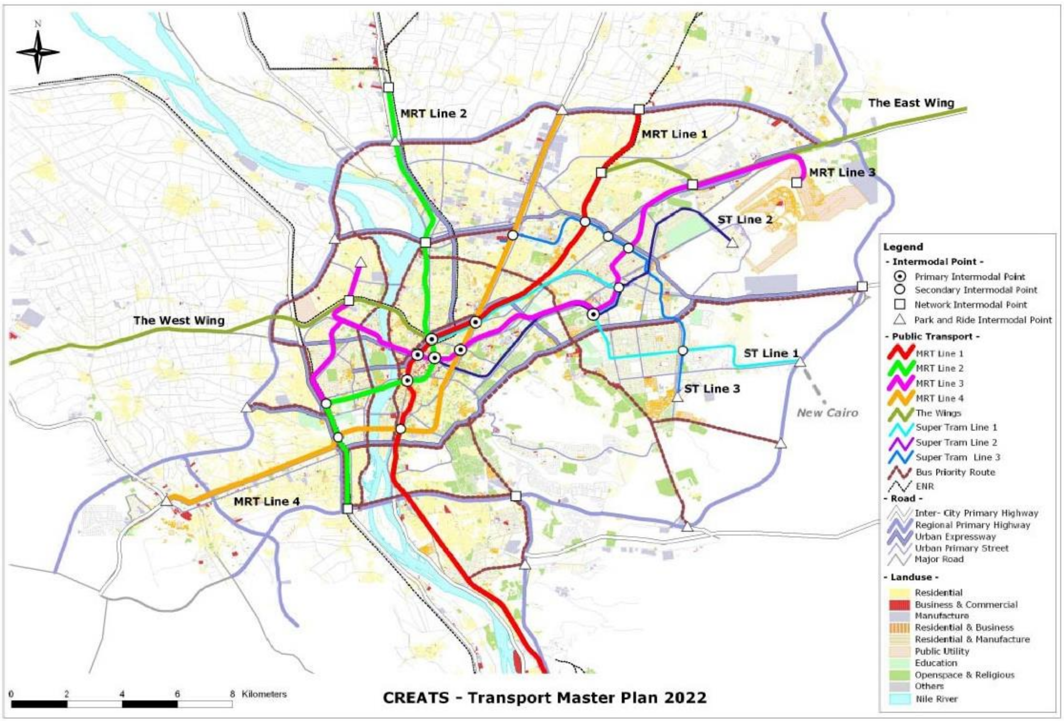

Figure 1. CREATS-Cairo transport master plan 2022

Modelling MMTS requires a comprehensive approach that integrates mathematical optimization, simulation techniques, and behavioural modelling [12]. Various studies have explored rule-based decision models, agent-based simulations, and real-time data-driven methodologies to optimize MMTS performance [13]. While some models focus on minimizing travel costs and improving route efficiency, others emphasize network resilience, critical node identification, and adaptive transport planning. The implementation of optimization-based MMTS frameworks not only improves traffic flow and commuter experience but also enhances the system's ability to respond to disruptions and changing travel demands.

Although substantial research has been conducted on MMTS modelling, there remains a need for a comprehensive review that synthesizes different modelling approaches and their strengths, limitations, and real-world applications. This paper aims to bridge that gap by providing a systematic review of MMTS modelling implementation. The authors hope that this review will serve as a valuable resource for transportation researchers, urban planners, and policymakers in designing, implementing, and improving MMTS models that optimize travel efficiency, account for traveller behaviour, and ensure network resilience in the face of growing urban mobility challenges.

2. LITERATURE REVIEW

Wang et al. [14] introduced a mathematical framework aimed at optimizing the integration of various public transportation modes, namely general on-demand services, local on-demand options, and fixed-schedule transit. Utilising Continuous Approximation (CA) methods, the authors develop a system-state equilibrium model that considers the dynamic interplay between travellers' rational choices and agency service levels, resulting in a unique equilibrium state. Extensive numerical experiments are conducted to test the model's effectiveness, validate and to analyse the impact of various design variables under different demand scenarios. Through the simulations, the model demonstrates that such an integrated system can significantly reduce overall travel costs and improve service levels, particularly by emphasizing the role of local on-demand services in enhancing last-mile connectivity. The findings indicate that adjusting the distribution of transportation services based on demand intensity leads to optimal societal benefits, affirming the value of combining different mobility solutions to better meet traveller's needs.

Compared to Wang's system-state equilibrium model, the study by Ma et al. [15] presents a more economically detailed bi-level framework that incorporates multiple user classes and actual fare data, thereby enabling a deeper understanding of the strategic behaviour of both public and private operators in a competitive environment.

The study by Ma et al. [15] presents a comprehensive economic analysis of a multi-modal transportation system, integrating bus, metro, and ride-sourcing services through a tractable bi-level model represented as a network, as illustrated in Figure 2. The study specifies a sample size of 6000 travellers categorised into different user classes. These user classes were determined based on their values of time (VOT), which were uniformly and normally distributed as part of the analysis. The validity of the model in the study is reinforced by its calibration with real-world data like Uber and Google Maps, ensuring relevance to actual transportation scenarios. Furthermore, the model's robustness is enhanced through comparative statics that assess the impact of changing system parameters and sensitivity analyses that evaluate the stability of results under different conditions.

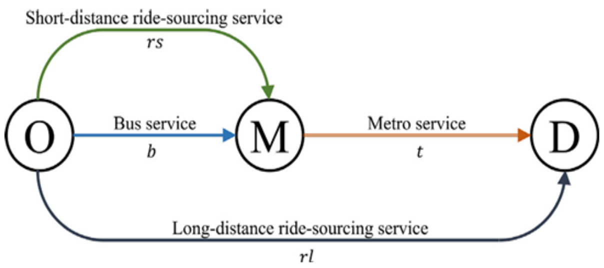

Figure 2. Network representation options

Key findings from the analysis indicate that the stochastic user equilibrium (SUE) model provides a more conservative estimate of the ride-sourcing operator's profit, and the total system travel cost compared to the deterministic user equilibrium (DUE) model. Sensitivity analysis reveals that travellers with longer total travel distances are more likely to utilize short-distance ride-sourcing services, suggesting that ride-sourcing operators should enhance service provision in suburban areas. The study also highlights the complex interplay between both operators, showing that optimal fare and frequency adjustments in public transit, prompted by the presence of ride-sourcing services, may lead to less traveller-friendly outcomes. Moreover, simultaneous optimization of operational strategies by both service providers can yield improved system performance, increase ride-sourcing profits while reduce total system costs.

While Ma's work relies on synthetic distributions and demand-based modeling, Aravinthan and Deepak [2] adopt an empirically grounded approach, validated through real-world traffic conditions, time-delay studies, and walkability assessments. Their modeling method incorporates various empirical data, including traffic volume studies to estimate passenger car units (PCUs), walkability index assessments to evaluate pedestrian infrastructure, and time-delay studies to measure travel times across different transport modes (2-wheelers, 4-wheelers, para-transit, and buses/metro) during peak hours. Additionally, origin-destination surveys are used to analyze travel patterns, and cost analyses assess the cost-effectiveness of each mode. The use of quantitative data enhances the model's credibility and validity.

Key findings show that time and speed delays are particularly pronounced during peak traffic hours, with an observed 30% increase in delays during the evening compared to morning times. The MMTS demonstrated that integrating modes such as two-wheelers, four-wheelers, paratransit, and buses/metro leads to significant time and cost savings compared to using single modes of transport. Specifically, while paratransit emerged as the most expensive mode with similar travel times to owned vehicles, the combination of multiple transportation modes provided a more efficient and cost-effective travel solution. Furthermore, the study highlights the importance of a well-designed schedule that optimizes the timing between connecting modes to mitigate wait times, thereby enhancing the overall usability and attractiveness of public transport options. Overall, the findings support the adoption of multimodal networks to facilitate more efficient urban transit systems, reduce road congestion, and improve commuter satisfaction.

In contrast to Aravinthan's data-intensive approach, Jafari et al. [12] employed an agent-based simulation calibrated with regional travel behaviour data to model complex system interactions at the individual level. Next, this research implements an activity-based and agent-based transport model for Greater Melbourne, utilizing the MATSim simulation toolkit to achieve a comprehensive representation of multi-modal transportation. The model incorporates a range of travel modes, including active transport like walking and cycling, and is calibrated against real-world data to ensure accuracy. The sample size of 15,038 commute trips was selected from a total of 92,725 trips in the 2012-2016 VISTA dataset to estimate utility function parameters in the agent-based model.

The data focused on mandatory trips within Greater Melbourne using one of four modes: driving, public transport, walking, or cycling, to minimize the influence of non-commute factors. The outcomes indicate that the calibrated model successfully mirrors observed travel behaviours, such as mode share percentages and traffic volumes, demonstrating its effectiveness for evaluating transportation interventions. Specifically, the model outputs reflect realistic travel times, road usage patterns, and passenger flows, thus providing a valuable tool for examining the effects of potential changes in urban transport infrastructure and policies.

While Jafari simulated travel behaviour, Gu et al. [16] advanced this approach by introducing a Weibit-based model that explicitly accounted for mode and route similarity—an improvement over traditional logit models commonly used in agent-based frameworks. The paper models the vulnerability of multi-modal transportation networks using the Weibit-based combined modal split and traffic assignment (CMSTA) model that captures travel behaviour across various modes and routes. It employs advanced Weibit choice models to account for the complexity of travel behaviours that involve both mode choice (e.g., choosing between metro, bus, or private car) and route choice (e.g., selecting specific paths within the chosen mode). Key findings indicate that the proposed Weibit-based accessibility measures provide a more accurate assessment of network vulnerability by considering the similarities between routes and modes, which traditional logit-based models often overlook. The model demonstrates superior performance in vulnerability analysis, particularly under scenarios with heterogeneous travel times, and highlights the importance of encompassing both mode and route choices to avoid overestimating vulnerability. Numerical experiments based on a simplified multi-modal network in Hong Kong substantiate the effectiveness of the proposed approach, showcasing its applicability in real-world contexts.

Building on this, Gu and Chen [17] extended the Weibit framework to customized bus (CB) services, incorporating user loyalty dynamics through the Dogit model, which marked a significant shift from standard utility-based models. Specifically, a nested Weibit model is used to evaluate passenger choice, incorporating perceived disutility across multiple transport modes while accounting for both mode similarity and heterogeneity. Additionally, the study integrates a Dogit model to capture the behaviour of loyal CB passengers, who, due to their subscription-based commitment, tend to disregard alternative transport modes when making travel decisions.

The findings emphasise the critical role of passenger loyalty in shaping mode choice behaviour, revealing that loyal CB subscribers are significantly less likely to shift to other transport options. This insight leads to distinct demand patterns for CB services. Moreover, the study highlights that integrating loyalty schemes into transit models can enhance service design, improve network performance, and optimize pricing strategies for CB operations. These results emphasize the importance of understanding traveller loyalty and mode characteristics in the development of efficient and sustainable urban transit solutions.

Whereas Gu focused on mode-level behavioural nuances, Nourmohammadi et al. [18] turned toward macro-level dynamic traffic modeling, integrating structural data such as the General Modeling Network Specification (GMNS) to simulate congestion and support operations across the Melbourne network, which ensured ease of data sharing and interpretation. The model incorporates 2077 nodes and 4223 links, along with a time-dependent origin-destination demand matrix reflecting 330,000 commuting trips during morning peak hours. It effectively captures the dynamics of traffic congestion and includes various data inputs such as network geometry, traffic control information, and traveller behaviour models. It illustrates the effectiveness of simulation-based dynamic traffic assignment methodologies in understanding and predicting traffic patterns in urban environments.

The study highlights the significance of integrating diverse data sources—including publicly available datasets (e.g., Google Maps and OpenStreetMap)—to accurately reflect the characteristics of the transportation network. This integration aids in validating the model's structure and performance. The developed model has the potential to be utilised in various applications within transportation network design and traffic operational management, such as corridor management, pricing strategies, and emergency management scenarios.

While Nourmohammadi modeled the full network, the study conducted by Wang et al. [19] focused on identifying critical nodes in MMT networks using a modified weighted k-shell (MWKS) method. MWKS model integrates both the network topology and traffic demand, considering the differential contributions of multi-order neighbour nodes represented by passenger volume and the concept of transportation corridors. The MWKS model aims to reflect the interactions between nodes in a transportation corridor, which traditional methods may overlook. Validation through a real transportation system in Zhejiang Province, China, showed that MWKS outperformed traditional methods and other k-shell-based approaches, accurately predicting crucial nodes that could lead to significant disruptions if compromised. The proposed contribution attenuation coefficient enhanced the assessment of node importance by reflecting the varying influences of multi-order neighbour nodes based on passenger volume and traffic dynamics. Additionally, the model exhibited a higher potential for cascading failures, demonstrating its robustness and reliability in practical applications.

On the other hand, Dixit et al. [20] developed a multi-modal transit route choice model using smart card data from Amsterdam to analyse the impact of a new metro line introduced in July 2018. By comparing pre- and post-introduction data, the research assesses changes in travel behaviour and validates the model through external testing of parameters. Despite discrepancies in parameter values between the two timeframes, the transferred model demonstrated satisfactory predictive performance, achieving a First Preference Recovery rate of 71.5% and a Mean Absolute Percentage Error (MAPE) of 0.3% for mode shares compared to observed choices. Overall predictive accuracy remained comparable to the locally estimated model, with less than a 10% increase in error for route and link-level predictions. The findings indicate that excluding important variables hinders predictive performance, while the inclusion of different modes of transit like bus and trams in model specifications did not improve transferability, suggesting context-specific considerations for overlaps in transit modelling.

Lastly, research conducted by Othman et al. [13] explained about the SUMMIT (Singapore Urban Multi-Modal Integrated Transport Simulator) which employs an agent-based simulation model to replicate the behaviours and interactions of commuters during unplanned disruptions in Singapore's Mass Rapid Transit (MRT) system. Each commuter is modelled as an autonomous agent, making decisions based on real-time data and environmental factors, which allows for an accurate representation of commuter responses to service interruptions.

Table 1. Summary of key findings from each modelling system

Ref.	Modelling System	Key Findings
[14]	Continuous Approximation (CA)	Demand-sensitive service distribution improves travel efficiency and last-mile connectivity.
[15]	Bi-level model (DUE & SUE)	Suburban ride-sourcing demand is influenced by trip length; SUE model provides a conservative profit estimate.
[2]	Parameters: Walkability index, Traffic Volume, Time and Delay Analysis, Cost Analysis	Integrated modes reduce travel time, cost, and congestion if schedules are optimized.
[12]	Activity-based and agent-based model (MATSim)	The model effectively reflects real-world travel behaviours and traffic volumes.
[16]	Weibit-based CMSTA model	Provides more accurate accessibility assessment compared to logit models.
[17]	Dogit model and Nested Weibit model	Traveller loyalty affects mode choice, influencing pricing and network performance.
[18]	Simulation-based dynamic traffic assignment (DTA) models	Integrates large-scale real-world data for traffic analysis and planning.
[19]	Modified weighted k-shell (MKWS)	Improved prediction of network disruptions and cascading failures.
[20]	Multi-modal transit route choice model	High accuracy in predicting travel behaviour shifts post-metro introduction.
[13]	SUMMIT (Agent-Based Model)	Real-time information dissemination is crucial in mitigating transit delays.

The outcomes of the model reveal that while bridging bus services effectively reduce crowding at train stations, they can inadvertently lead to longer travel times due to high demand for these buses. Additionally, the results underline the importance of timely dissemination of information during disruptions, which can significantly mitigate negative impacts on commuters' experiences. Though simulation-based, its agent-level decision-making is grounded in realistic conditions, making it suitable for planning emergency responses. Compared to static equilibrium models like Wang et al. [14], SUMMIT provides richer behavioural insights. A comparative summary of the key modelling approaches and findings from the reviewed studies is presented in Table 1.

While the focus of this review is primarily on passenger mobility, freight and logistics are also critical components of MMTS, particularly in urban areas. Efficient freight integration aligns with the objectives of United Nations Sustainable Development Goal 11 (SDG 11): Sustainable Cities and Communities, which emphasizes the need for inclusive, safe, resilient, and sustainable urban transport. Incorporating freight-oriented multimodal solutions such as urban consolidation centers, last-mile delivery innovations, and blockchain-enabled coordination mechanisms enhances urban transport efficiency and reduces emissions, congestion, and environmental impact. The inclusion of freight considerations in this review, particularly within the context of blockchain-based modelling (Section 3.3.2), supports a more holistic understanding of sustainable MMTS planning in line with SDG 11 targets.

3. FINDINGS

3.1 Strength

The findings table provides a comparative analysis of ten key studies on MMTS modelling, focusing on their strengths. Table 2 categorizes these studies based on their modeling approach—including optimization models, agent-based simulations, travel behaviour analysis, and resilience assessment—and highlights significant contributions and limitations.

Table 2. Strength of each research

Ref.	Strength
[14]	Proposes a mathematical optimization framework for MMTS
	Uses continuous approximation for demand-based design
[15]	The bi-level optimization model considers both users and operators
	Evaluates stochastic and deterministic models
[2]	Evaluate MMTS using traffic volume, walkability, and cost analysis
	Highlights integration benefits in reducing congestion
[12]	Integrates agent-based and activity-based modelling
	Incorporate both motorized and non-motorized transport
[16]	Advanced modeling approach
	Capture both route and mode choices accurately
[17]	Uses logit and Nested Weibit models for traveller loyalty
	Address mode similarity and heterogeneity in decision-making
[18]	Provides an open-source dataset for MMTS research
	Uses GMNS for interoperability and large-scale simulations
[19]	Combines network topology and traffic demand for node analysis
	Effective in predicting network disruptions
[20]	Uses smart card data for external validation
	High predictive accuracy for commuter behaviour shifts
[13]	Real-world data calibration enhances accuracy
	Evaluating disruption impacts and mitigation strategies

Several studies, including Wang et al. [14] and Ma et al. [15], employed mathematical optimization models to efficiently integrate multiple transport services, aiming to reduce overall travel costs and enhance last-mile connectivity. Other studies, such as Jafari et al. [12] and Othman et al. [13], utilized agent-based and simulation-based models to replicate real-world commuter behaviour and assess network performance under varying conditions. The table also highlights research focused on network resilience and critical node identification, exemplified by Gu et al. [16] and Wang et al. [19], underscoring the importance of modeling network disruptions and understanding system vulnerabilities. Additionally, Gu and Chen [17] and Dixit et al. [20] explored travel behaviour modeling by incorporating loyalty-based mode choices and validating smart card data to analyze commuter preferences and transit route selection.

3.2 Weakness

Despite the strength of each research, some limitations were identified. The following sections offer detailed, elaborated solutions to these challenges to support future research and policy-making in this domain. Table 3 shows the limitations of each research and provides a thematic classification for a statistical overview.

Table 3. Thematic classification of weaknesses

Ref.	Weakness	Thematic Classification
[14]	Heavy reliance on demand forecasting	Data Limitations
	Assumes centralized on-demand forecasting	Model Assumptions
[15]	Excludes private vehicle users	Scope Limitations
	Assuming fully rational traveller decisions	Behavioural Considerations
[2]	Limited inclusion of emerging transport options like micromobility	Scope Limitations
	Lacks policy-based evaluations	Scope Limitations
[12]	Limited scope for non-work trips	Scope Limitations
	High computational complexity	Computational Challenges
[16]	Simplified network used in numerical experiments	Model Assumptions
	Does not consider real-time changes	Model Assumptions
[17]	Limited empirical validation	Data Limitations
	Does not consider short-term fluctuation in passenger demand	Behavioural Considerations
[18]	Possible inconsistencies in data sources	Data Limitations
	Does not focus on behavioural pattern	Behavioural Considerations
[19]	Dependent on assumed traffic demand values	Model Assumptions
	Lacks analysis of cascading failures in extreme scenarios	Scope Limitations
[20]	Model parameters were unstable over different periods	Data Limitations
	Error in route-level prediction due to assumptions-based input	Model Assumptions
[13]	Limited generalizability beyond Singapore	Scope Limitations
	Static demand elasticity assumption	Model Assumptions

The thematic analysis of weaknesses across 10 reviewed studies revealed a total of 20 distinct limitations, averaging 2.0 weaknesses per study, with a median of 2. As illustrated in

Figure 3, the most frequently occurring themes were Model Assumptions and Scope Limitations, each appearing six times. These categories reflect common oversights such as overly simplified transport network structures and narrow focus areas excluding certain trip types or emerging transport modes.

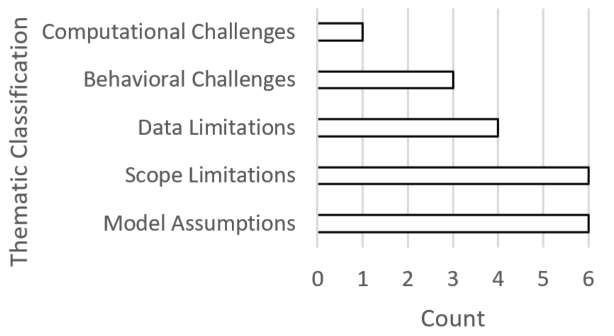

Figure 3. Count of weaknesses by theme

Data limitations and behavioural challenges followed, each with four and three instances, respectively, highlighting issues like overreliance on forecasting or unrealistic assumptions about traveller rationality. The least addressed challenge was Computational Complexity, cited only once, suggesting a potential gap in addressing the practical feasibility of implementing advanced simulation models at scale. This distribution indicates that while conceptual and scope-based shortcomings are well-recognized, operational scalability and technical feasibility are often underexplored in current MMTS research.

3.3 Solution and recommendations

As the complexity of urban mobility grows, modelling and evaluating multimodal mass transit systems (MMTS) presents both opportunities and challenges. While current studies contribute valuable insights, they often face recurring limitations across dimensions such as data reliance, model assumptions, behavioural realism, policy simulation, and computational feasibility. The following sections offer detailed, elaborated solutions to these challenges to support future research and policy-making in this domain.

3.3.1 Overcoming data limitations

Several studies [14, 17, 18, 20] highlight overreliance on forecasting or data inconsistencies as a key limitation. Thus, to address this issue, the following researchers is suggested to integrate real-time and adaptive data into their models. Traditional forecasting can be augmented with real-time inputs such as GPS data, mobile phone tracking, and smart card usage. This allows demand models to adapt dynamically to current travel patterns, reducing prediction errors and enhancing model reliability. Besides that, data validation protocols should be standardized. Studies such as Nourmohammadi et al. [18] suffer from inconsistencies due to the integration of data from diverse sources. Implementing data cleaning procedures, cross-validation, and source triangulation can help ensure accuracy and consistency. Several validation techniques can be applied, including range checks, semantic validation, and consistency checks, among others [21].

3.3.2 Improving model assumptions

Simplifying assumptions often undermine model realism. Studies like [13, 14, 16, 19] assume centralized control, static demand, or simplified networks. Firstly, decentralized governance modelling can replace assumptions of a central authority, which is a limitation in Wang's research [14]. Urban transit involves multiple stakeholders (e.g., government departments, private operators, freight handlers, and regulatory bodies), each with distinct goals and data ownership. This discrepancy undermines the practicality and scalability of centralized models. The implementation of a blockchain-based system able to address the issue by implementing a "one-bill coverage system" where each transport entity (carriers, shippers, consignees) operates autonomously but shares information through a shared blockchain ledger. This enables decentralized decision-making and mutual oversight, mitigating the trust and coordination challenges of centralized control [22].

Secondly, a real-world network application is necessary for models [16], which use simplified networks. Applying the methodology to actual transport networks with heterogeneous nodes, congestion effects, and multimodal transfers will improve accuracy. This is supported by recent advances such as the THAN model, which demonstrates the value of leveraging real-world heterogeneous graph structures and multimodal transport data for improved recommendation accuracy in navigation systems [23].

Thirdly, scenario-based modelling and stress tests can address oversimplified assumptions in Wang's research [19]. Simulating extreme events like infrastructure failures or demand surges reveals system vulnerabilities and resilience strategies, as demonstrated in scenario-based studies of road transport performance [24].

Lastly, dynamic demand elasticity models can improve realism. Static assumptions in Othman's research [13] fail to capture changes in rider behaviour in response to service quality, pricing, or time. Dynamic demand elasticity models, unlike static models, account for how consumer behaviour and demand change over time, incorporating factors like intertemporal rationality and the adjustment process of demand. They are crucial for understanding how consumers react to price changes, income shifts, and other market dynamics, and for making informed pricing and production decisions [25, 26].

3.3.3 Expanding behavioural realism

Traveller decision-making is often modelled as fully rational, as seen in references [15, 17]. This approach oversimplifies real-world behaviour. Short-term behavioural changes, such as sudden spikes in ridership or responses to service alerts, should be incorporated. With higher-frequency data, models can adjust their predictions or decisions more quickly in response to real-time changes. For instance, if smart card data reveals a sudden increase in trips to a specific location, a model can quickly update its traffic flow predictions [27] which makes the journey smoother for travellers or users.

Furthermore, future research should explicitly consider the concept of bounded rationality in travel behaviour. Bounded rationality acknowledges that individuals make decisions with limited information, cognitive resources, and time, often leading to "satisficing" rather than optimizing choices [28]. This is evident in mode choice, where commuters may not always select the objectively fastest or cheapest option but instead rely on habits, perceived convenience, or incomplete information. Models can better reflect this by incorporating behavioural rules, heuristics, and prospect theory, moving beyond the assumption of perfect rationality. Agent-based models, as highlighted in this review, are particularly suitable for simulating boundedly rational behaviour by allowing agents to have heterogeneous decision-making processes and learning mechanisms.

3.3.4 Policy simulation framework

Integrating policy simulation frameworks could be a solution to the lack of policy evaluation in Aravinthan and Deepak's research [2]. These frameworks enable the modelling and testing of hypothetical or actual policy interventions under a range of conditions, allowing stakeholders to anticipate both intended and unintended consequences. Real-world transit planning must balance economic, environmental, and social goals. A policy evaluation module allows for multi-criteria decision analysis (MCDA) to explore trade-offs, such as between cost efficiency and environmental sustainability or equity versus coverage, as MCDA is particularly suited to managing multidimensional indicators in sustainability assessments [29].

3.3.5 Handling computational challenges

High computational complexity can make advanced models like those in Jafari et al.'s research [12] impractical for large-scale deployment. To address this, incorporating parallel and cloud computing techniques, such as those evaluated in high-performance computing (HPC) integrated multi-agent simulation platforms, can significantly reduce runtime and enhance scalability, enabling efficient execution of complex, multi-scenario transport analyses [30].

4. DISCUSSION

4.1 Strength

The reviewed studies demonstrate significant methodological advancements in MMTS modelling, particularly in optimization, travel behaviour analysis, and network resilience. Mathematical optimization models (e.g., Wang et al. [14]; Ma et al. [15]) have played a crucial role in enhancing service integration, reducing congestion, and optimizing public transit operations. These models allow transportation planners to balance demand and supply efficiently, improving travel time reliability and cost-effectiveness. Additionally, agent-based and activity-based models (e.g., Jafari et al. [12]; Othman et al. [13]) have been instrumental in simulating real-world commuter behaviour under different scenarios, providing valuable insights for policy interventions and transit planning.

A key strength observed in many studies is the integration of real-world data for model validation. For instance, Dixit et al. [20] employ smart card transaction data to evaluate the accuracy of transit route choice models, demonstrating high predictive validity. Similarly, Nourmohammadi et al. [18] utilize General Modelling Network Specification (GMNS) to create a comprehensive, open-source MMTS dataset, enabling cross-comparison and replication of results. These data-driven approaches enhance the credibility and applicability of MMTS models, making them more relevant for real-world deployment. Additionally, several studies focus on network resilience and vulnerability analysis, addressing critical infrastructure weaknesses in MMTS. Gu et al. [16] and Wang et al. [19] introduce advanced computational models to identify critical nodes and potential failure points, providing a foundation for disaster preparedness and risk mitigation strategies. These studies highlight the need for robust, adaptive transportation networks capable of withstanding disruptions such as natural disasters, technical failures, or sudden demand shifts.

4.2 Limitations

Despite these strengths, several limitations persist across the studies.

4.2.1 Limited geographic generalizability

A recurring issue is limited geographic generalizability, where models are calibrated for specific urban contexts (e.g., Othman et al. [13] focus on Singapore’s public transport system). This restricts their applicability to other cities with different transport infrastructures and commuter behaviours. This challenge is also highlighted in research by Waddell [31], which discusses the difficulties in adapting academic models like UrbanSim for practical use in various U.S. cities. His study emphasizes the need to balance theoretical validity with operational requirements, reinforcing the argument that location-specific transport models often require significant adjustments before they can be applied to different urban environments.

The challenge of applying models developed for specific urban contexts to other cities necessitates a shift towards more flexible and adaptable modeling frameworks. Instead of building monolithic models, future research should focus on developing modular components that represent fundamental aspects of transport systems and commuter behaviour. These modules could be designed with adaptable parameters that can be calibrated using local data. For instance, a mode choice module could incorporate socio-economic factors and travel preferences that can be adjusted based on city-specific surveys and census data which had been done in the City of Warsaw [32]. Recent work in transfer learning within transportation science could offer methodologies to adapt models trained on one city's data to another with minimal retraining. This involves identifying shared representations across different urban environments.

Besides that, emphasize the use of extensive local data for calibrating and validating models. This includes not just traditional travel surveys but also leveraging emerging data sources like smart card data, mobile phone location data, and social media data (while respecting privacy concerns). Advanced statistical and machine learning techniques can be employed to extract meaningful insights from these diverse datasets and fine-tune model parameters for specific urban environments. Research on federated learning (FL) could also be explored, allowing models to be trained on decentralized data from multiple cities without directly sharing sensitive information. Research conducted by Betul et al has proven that FL strategies can solve privacy and confidentiality concerns, particularly for high-risk applications [33].

4.2.2 Computational complexity

Additionally, according to Bastarianto et al. [34] computational complexity is a major issue since it poses a challenge for large-scale implementation, particularly for agent-based and activity-based models such as the model developed by Jafari et al. [12], which requires substantial processing power. Besides that, Jafari et al. [12] and Othman et al. [13] models also require high computational resources, making them difficult to implement in cities with complex, multimodal transit systems. To address this, future research should focus on developing scalable MMTS models that maintain high accuracy while reducing computational demands. One of the solutions is to explore methods to simplify model structures and aggregate individual behaviours where appropriate, without significant loss of accuracy. This could involve using representative agent groups instead of simulating every individual or employing coarser spatial and temporal resolutions for certain analyses. Research in macroscopic traffic flow modelling and system dynamics offers techniques for representing aggregate behaviour efficiently.

On the other hand, advancements in HPC and parallel processing techniques to handle the computational load of complex models also a solution to the computational complexity which had been highlighted in previous section. Cloud computing platforms offer scalable resources that can be utilized for large-scale simulations. Recent developments in GPU-accelerated computing can significantly speed up simulations, particularly for agent-based models [35].

4.2.3 Incorporating behavioural realism

Many studies also assume static demand elasticity or rational traveller behaviour, which may not accurately reflect real-world commuter decisions. For instance, Ma et al. [15] does not account for behavioural uncertainties in user preferences, which could affect mode choice predictions. Incorporate insights from behavioural economics and psychology to model more realistic traveller preferences and decision-making processes. This includes accounting for factors like bounded rationality, cognitive biases, habits, and the influence of social networks. Recent research in behavioural travel modeling is exploring the use of concepts like prospect theory and regret minimization to better understand mode choice and route selection [36].

4.2.4 Emerging transport trends

Furthermore, most studies do not fully incorporate emerging transport trends such as autonomous vehicles, e-bikes, or Mobility-as-a-Service (MaaS), limiting their relevance for future transport planning. This is particularly evident in the case of MaaS, where its integration with public and private transport modes remains an emerging field of research, with most relevant studies only recently published [37].

Recent research promotes integrating these trends through platform-based modeling and multi-actor digital ecosystems, which simulate collaboration between public and private stakeholders. The digital twin's (DT) paradigm supports this by creating a virtual sandbox where new technologies (like AVs or MaaS platforms) can be stress-tested under different policy or market conditions before real-world deployment. One of example implementing DT is in research conducted by Yu et al. [38], who presented real-world applications of digital twin technology as an effective approach for developing autonomous driving (AD) systems, enabling the creation of comprehensive, accurate, and reliable virtual models of the physical environment.

4.2.5 Policy and governance

Lastly, policy and governance considerations are underrepresented in MMTS research. While some studies analyse economic impacts and fare optimization, few integrate policy-driven regulations, urban transport policies, or government intervention strategies [39]. For instance, Aravinthan and Deepak [2] focus on MMTS design for congestion reduction but does not account for regulatory frameworks or sustainable transport incentives. Future research should incorporate multi-level policy analysis, including pricing policies, public transit subsidies, land use and infrastructure investments, to develop more comprehensive MMTS planning frameworks.

To illustrate the potential of a more integrated approach, Pozoukidou's research [40] offers a valuable example. While the study makes significant steps in linking transport planning with urban development, it also highlights a key prerequisite for successful implementation: the essential need for comprehensive data availability, well-structured data management, and strict standardization across all stages of the modelling process.

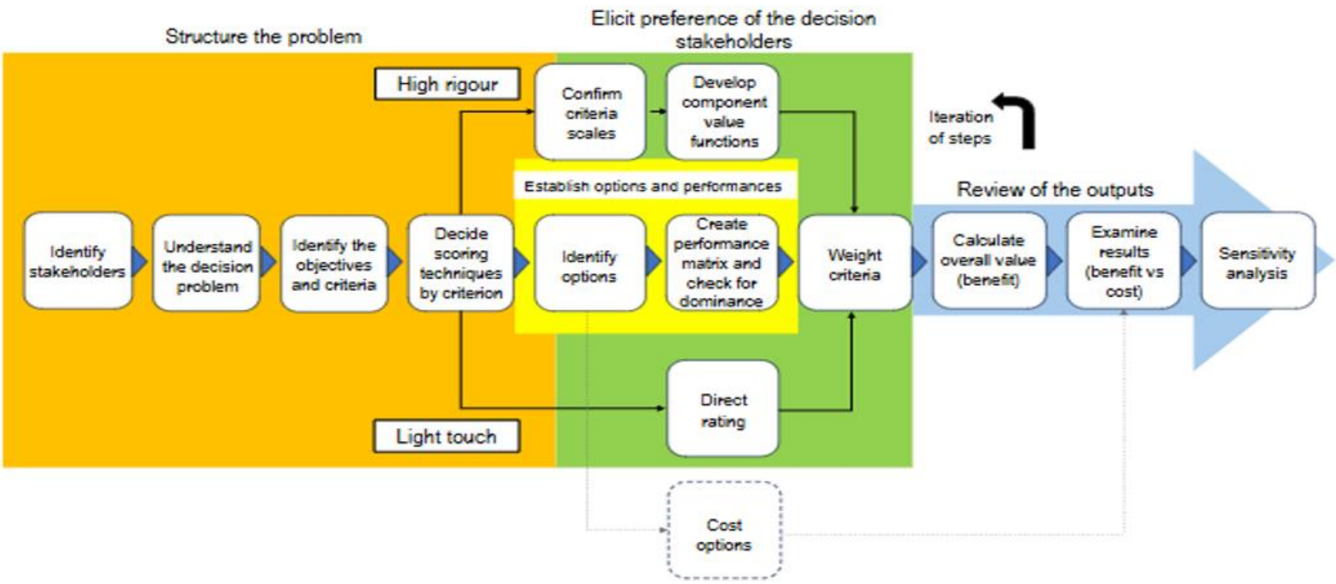

Figure 4. MCDA flowchart

Effectively translating model outputs into policy requires a shift beyond simply providing raw predictions. It necessitates the development of frameworks that facilitate the interpretation and application of model results within a policy context. For example, the use of models to simulate the impact of new infrastructure, as seen in Dixit et al. [20], provides a basis for policy decisions regarding investments in transport projects. However, the review also indicates a need for more explicit frameworks for policy translation.

As highlighted in the recommendations, integrating policy simulation frameworks and MCDA is crucial to ensure that models inform well-rounded and effective policy decisions. As illustrated in Figure 4, the MCDA process can be broadly divided into four main blocks: 'Structure the problem,' 'Establish options and performance,' 'Elicit preferences of the decision stakeholders,' and 'Review the output.' By systematically structuring the decision-making process, as outlined in the MCDA framework, policymakers can better incorporate model outputs alongside other relevant factors (e.g., social, environmental, economic) to make informed and transparent decisions regarding MMTS planning and implementation. Furthermore, close collaboration between model developers, urban planners, and policymakers is essential to ensure that models are designed to address relevant policy questions and that the results are communicated in a clear and accessible manner.

4.3 Cross-cultural and regional influences on MMTS modelling

This review reveals an opportunity to further explore how MMTS modelling approaches may reflect underlying regional or cultural contexts. While the studies utilize diverse methodologies, there is limited explicit discussion on whether distinct "Western" versus "Asian" modelling traditions exist. For example, several studies (Othman et al. [13] on Singapore, Wang et al. [19] on China, as well as Gu et al. [16], and Gu and Chen [17] on Hong Kong) emphasize high-density urban environments and public transit efficiency, potentially reflecting the prioritization of collective mobility in Asian cities. In contrast, while studies like Dixit et al. [20] focus on European cities, there's less emphasis on the same high-density integration challenges. Future research could investigate whether Western models place a relatively higher emphasis on individual mode choice and private vehicle integration. Further analysis is needed to determine if these observed differences are statistically significant and how they influence model transferability.

Cultural and urban form differences significantly impact the generalizability of MMTS models. The models are calibrated for specific urban contexts (e.g., Othman et al. [13] for Singapore's public transport system), which restricts their applicability to other cities with different transport infrastructures and commuter behaviours. For instance, the high-density, mixed-use development patterns common in many Asian cities facilitate efficient public transport and active travel, which may explain the focus of some models on optimizing these modes. Conversely, cities with sprawling suburban development may require models that give greater weight to private vehicle integration and long-distance commuting patterns. Future research should explicitly incorporate urban morphology and cultural factors (e.g., attitudes towards public transit, walking, and cycling) as parameters in MMTS models to enhance their adaptability across diverse contexts. This could involve developing typologies of urban form and cultural profiles to inform model calibration and transferability.

5. CONCLUSIONS

This review has critically examined contemporary modelling approaches in MMTS, with a focus on optimization, travel behaviour analysis, and network resilience. The findings highlight significant advancements in equilibrium modelling, agent-based simulations, and demand-responsive frameworks, which collectively contribute to improved MMTS performance. The integration of real-world data sources and advanced computational methodologies has enhanced the accuracy of MMTS models, allowing for better planning and policy implementation.

Despite these advancements, several critical gaps remain. Many studies lack scalability due to the high computational complexity of agent-based and dynamic traffic assignment models, limiting their application in large-scale urban networks. Furthermore, most models assume static travel behaviour, failing to incorporate real-time adaptability that reflects evolving commuter preferences and traffic conditions. Additionally, policy considerations and emerging mobility solutions, such as autonomous vehicles, shared micromobility, and MaaS, remain underexplored, reducing the practical applicability of many MMTS frameworks. To advance the field, future research should prioritize:

1) Cross-Regional Validation-Testing MMTS models across different geographic contexts to ensure broad applicability.
2) Scalability Enhancements-Optimizing computational models to enable large-scale MMTS applications.
3) Real-Time Adaptability-Integrating real-time data analytics and predictive modelling for dynamic system adjustments.
4) Inclusion of Emerging Mobility Trends-Expanding MMTS frameworks to include micromobility, electric shared transport, and MaaS platforms.
5) Policy and Governance Integration-Incorporating regulatory mechanisms, pricing strategies, and governance models to improve MMTS implementation.

Among these proposed directions, Real-Time Adaptability emerges as the most urgent. The increasing availability of real-time data streams, coupled with advancements in predictive analytics and machine learning, presents an immediate opportunity to move beyond static assumptions of travel behaviour. In today's dynamic urban environments, where traffic conditions fluctuate rapidly and commuter preferences can shift in response to real-time information or disruptions, models that fail to incorporate this dynamism risk becoming quickly outdated and less effective for operational decision-making.

The increasing emphasis on real-time data integration and adaptive models highlight the importance of considering the maintenance requirements of real-time MMTS systems. These systems are not static tools; they require continuous data validation, model calibration, and system monitoring to maintain accuracy and reliability over time. This includes addressing challenges related to data quality, system resilience, and the development of automated monitoring and error detection tools.

Addressing this limitation has the potential for immediate impact on optimizing existing MMTS by enabling proactive adjustments to schedules, routing, and information dissemination, ultimately enhancing the commuter experience and network efficiency in real-time.

It's crucial to recognize that these future research directions are not mutually exclusive; rather, they are deeply interconnected and offer significant potential for synergistic advancements. For instance, enhancing the scalability of models will be essential to effectively implement real-time adaptability in large, complex urban networks. Similarly, incorporating emerging mobility trends like MaaS necessitates a strong understanding of evolving user behaviour, which can be significantly enhanced by real-time adaptability through the analysis of usage patterns and preferences.

Integrating emerging mobility trends, particularly MaaS and micromobility, presents unique challenges and opportunities for adapting existing MMTS models. For MaaS platforms, future research should explore the integration of decentralized technologies like blockchain to ensure secure and transparent verification of transactions and service usage across diverse providers within the MMTS ecosystem. This could enhance trust and facilitate seamless interoperability. Furthermore, current models often lack the granularity to capture the dynamic and localized nature of micromobility services. Addressing this requires developing methods to effectively integrate the high-volume, real-time data generated by e-scooters and shared bikes, including GPS trajectories, battery levels, and availability. This integration poses significant data management and processing challenges, demanding advancements in data fusion techniques and potentially requiring the development of new spatial-temporal modeling approaches. Understanding the interplay between these new modes and traditional public transport within existing MMTS frameworks is crucial for optimizing network design and ensuring equitable access.

Next, the success of cross-regional validation will be strengthened by developing more flexible and computationally efficient models that can be adapted to diverse data environments and policy landscapes. Ultimately, an overall approach that considers these interdependencies will be vital for developing the next generation of MMTS modelling frameworks, leading to more resilient, adaptive, and sustainable transport networks that effectively serve the evolving mobility needs of our cities. This review serves as a foundational reference for researchers, urban planners, and policymakers aiming to optimize MMTS for evolving transportation needs.

REFERENCES

[1] Jain, J., Khare, S. (2015). Multi modal public transportation system-Indore case study. International Journal of Scientific Engineering and Research, 3(9): 47-50. https://doi.org/10.70729/IJSER15468

[2] Aravinthan, K., Deepak, D. (2022). Modelling approach to develop a multimodal transportation network. In IOP Conference Series: Materials Science and Engineering, 1258(1): 012067. https://doi.org/10.1088/1757-899X/1258/1/012067

[3] Pandit, L., Knöll, M. (2019). Understanding multimodal accessibility parameters in diverse urban environments: A pilot study in Darmstadt. International Journal of Transport Development and Integration, 3(4): 317-330. https://doi.org/10.2495/TDI-V3-N4-317-330

[4] Dimitrakopoulos, G., Uden, L., Varlamis, I. (2020). Chapter 16-Transportation network applications. In: The Future of Intelligent Transport Systems. Elsevier, pp. 175-188. https://doi.org/10.1016/B978-0-12-818281-9.00016-4

[5] Elmenshawy, A., Idris, A., Nasr, A., Mohamed, A. (2024). Multimodal transportation planning for intercity travel between Alexandria and Borg Al Arab cities. International Journal of Transport Development and Integration, 8(3): 473-496. https://doi.org/10.18280/ijtdi.080311

[6] Ministry of Planning and Economic Development. (2023). 2030 Vision of Eygpt. https://mped.gov.eg/Files/Egypt_Vision_2030_English DigitalUse.pdf.

[7] Transport Department. (2024). Section 5: Public transport. Transport Department. https://www.td.gov.hk/mini_site/atd/2023/en/section5-1.html.

[8] Agarwal, P.K., Tanwar, R., Patel, S. (2024). Multimodal transportation system: Basic concept and challenges ahead. In Futuristic Trends in Construction Materials & Civil Engineering. IIP Iterative International Publishers, pp. 157-170. https://doi.org/10.58532/V3BJCE6P3CH1

[9] Ismail, Z., Sulaiman, S., Tuan Besar, T.B.H., Aminuddin, Z.M., Asmuni, S., Sulaiman, N.A., Abu Samah, S.E. (2024). Navigating urban mobility: The relationship between car consumption and public transport usage in Malaysia. Information Management and Business Review, 16(3S(I)a): 502-513. https://doi.org/10.22610/imbr.v16i3S(I)a.4148

[10] Arti, C., Sharad, G., Pradeep, K., Chinmay, P., Kumar, S.S. (2022). Urban traffic congestion: Its causes-consequences-mitigation. Research Journal of Chemistry and Environment, 26(12): 164-176. https://doi.org/10.25303/2612rjce1640176

[11] Chadalawada, R. (2022). Optimizing public transit networks an exploration of how multi-modal transportation systems can be integrated in smart cities. World Journal of Advanced Research and Reviews, 15(1): 829-841. https://doi.org/10.30574/wjarr.2022.15.1.0630

[12] Jafari, A., Singh, D., Both, A., Abdollahyar, M., Gunn, L., Pemberton, S., Giles-Corti, B. (2024). Activity-based and agent-based transport model of Melbourne: An open multi-modal transport simulation model for Greater Melbourne. Journal of Intelligent Transportation Systems, 1-18. https://doi.org/10.1080/15472450.2024.2372894

[13] Othman, N.B., Jayaraman, V., Chan, W., Loh, Z.X.K., Rajendram, R., Mepparambath, R.M., Agrawal, P., Ramli, M.A., Qin, Z. (2023). SUMMIT: A multi-modal agent-based co-simulation of urban public transport with applications in contingency planning. Simulation Modelling Practice and Theory, 126: 102760. https://doi.org/10.1016/j.simpat.2023.102760

[14] Wang, Y.N., Lin, X., He, F., Li, M. (2022). Designing transit-oriented multi-modal transportation systems considering travelers' choices. Transportation Research Part B: Methodological, 162: 292-327. https://doi.org/10.1016/j.trb.2022.06.002

[15] Ma, M.Y., Chen, Y.H., Liu, W., Waller, S.T. (2023). An

economic analysis of a multi-modal transportation system with ride-sourcing services and multi-class users. Transport Policy, 140: 1-17. https://doi.org/10.1016/j.tranpol.2023.06.008

[16] Gu, Y., Chen, A., Kitthamkesorn, S. (2022). Accessibility-based vulnerability analysis of multi-modal transportation networks with weibit choice models. Multimodal Transportation, 1(3): 100029. https://doi.org/10.1016/j.multra.2022.100029

[17] Gu, Y., Chen, A. (2023). Modeling mode choice of customized bus services with loyalty subscription schemes in multi-modal transportation networks. Transportation Research Part C: Emerging Technologies, 147: 104012. https://doi.org/10.1016/j.trc.2023.104012

[18] Nourmohammadi, F., Mansourianfar, M., Shafiei, S., Gu, Z., Saberi, M. (2021). An open GMNS dataset of a dynamic multi-modal transportation network model of Melbourne, Australia. Data, 6(2): 21. https://doi.org/10.3390/data6020021

[19] Wang, L., Zhang, S., Szűcs, G., Wang, Y. (2024). Identifying the critical nodes in multi-modal transportation network with a traffic demand-based computational method. Reliability Engineering & System Safety, 244: 109956. https://doi.org/10.1016/j.ress.2024.109956

[20] Dixit, M., Cats, O., van Oort, N., Brands, T., Hoogendoorn, S. (2024). Validation of a multi-modal transit route choice model using smartcard data. Transportation, 51(5): 1809-1829. https://doi.org/10.1007/s11116-023-10387-z

[21] Charles, E. (2024). Data validation techniques for ensuring data quality. https://www.researchgate.net/publication/384592714.

[22] Qian, X., Shen, L., Yang, D., Zhang, Z., Jin, Z. (2024). Research on multimodal transport of electronic documents based on blockchain. Big Data and Cognitive Computing, 8(6): 67. https://doi.org/10.3390/bdcc8060067

[23] Xu, A., Zhong, P., Kang, Y., Duan, J., Wang, A., Lu, M., Shi, C. (2022). THAN: Multimodal transportation recommendation with heterogeneous graph attention networks. IEEE Transactions on Intelligent Transportation Systems, 24(2): 1533-1543. https://doi.org/10.1109/TITS.2022.3221370

[24] Asgarpour, S., Hartmann, A., Gkiotsalitis, K., Neef, R. (2023). Scenario-based strategic modeling of road transport demand and performance. Transportation Research Record, 2677(5): 1415-1440. https://doi.org/10.1177/03611981221143377

[25] Fukasawa, T. (2024). The biases in applying static demand models under dynamic demand. Review of Industrial Organization, 65(2): 561-594. https://doi.org/10.1007/s11151-024-09946-0

[26] Selvanathan, S., Jayasinghe, M., Selvanathan, E.A., Rathnayaka, S.D. (2024). Dynamic modelling of consumption patterns using LA-AIDS: A comparative study of developed versus developing countries. Empirical Economics, 66(1): 75-135. https://doi.org/10.1007/s00181-023-02465-z

[27] Karami, Z., Kashef, R. (2020). Smart transportation planning: Data, models, and algorithms. Transportation Engineering, 2: 100013. https://doi.org/10.1016/j.treng.2020.100013

[28] Ramirez, H.G., Leclercq, L., Chiabaut, N., Becarie, C., Krug, J. (2021). Travel time and bounded rationality in travellers' route choice behaviour: A computer route choice experiment. Travel Behaviour and Society, 22: 59-83. https://doi.org/10.1016/j.tbs.2020.06.011

[29] Talukder, B., Hipel, K.W. (2021). Review and selection of multi-criteria decision analysis (MCDA) technique for sustainability assessment. In Energy Systems Evaluation (Volume 1) Sustainability Assessment. Cham: Springer International Publishing, pp. 145-160. https://doi.org/10.1007/978-3-030-67529-5_7

[30] Rousset, A., Herrmann, B., Lang, C., Philippe, L. (2016). A survey on parallel and distributed multi-agent systems for high performance computing simulations. Computer Science Review, 22: 27-46. https://doi.org/10.1016/j.cosrev.2016.08.001

[31] Waddell, P. (2011). Integrated land use and transportation planning and modelling: Addressing challenges in research and practice. Transport Reviews, 31(2): 209-229. https://doi.org/10.1080/01441647.2010.525671

[32] Luckner, M., Wrona, P., Grzenda, M., Łysak, A. (2024). Analysing urban transport using synthetic journeys. In 24th International Conference on Computational Science, Malaga, Spain, pp. 118-132. https://doi.org/10.1007/978-3-031-63783-4_10

[33] Yurdem, B., Kuzlu, M., Gullu, M.K., Catak, F.O., Tabassum, M. (2024). Federated learning: Overview, strategies, applications, tools and future directions. Heliyon, 10(19): e38137. https://doi.org/10.1016/j.heliyon.2024.e38137

[34] Bastarianto, F.F., Hancock, T.O., Choudhury, C.F., Manley, E. (2023). Agent-based models in urban transportation: Review, challenges, and opportunities. European Transport Research Review, 15(1): 19. https://doi.org/10.1186/s12544-023-00590-5

[35] Greengard, S. (2024). GPUs force CIOs to rethink the datacenter. https://www.informationweek.com/it-infrastructure/gpus-force-cios-to-rethink-the-datacenter.

[36] Van Wee, B. (2010). Prospect theory and travel behaviour: A personal reflection based on a seminar. European Journal of Transport and Infrastructure Research, 10(4). https://doi.org/10.18757/ejtir.2010.10.4.2902

[37] Utriainen, R., Pöllänen, M. (2018). Review on mobility as a service in scientific publications. Research in Transportation Business & Management, 27: 15-23. https://doi.org/10.1016/j.rtbm.2018.10.005

[38] Yu, B., Chen, C., Tang, J., Liu, S., Gaudiot, J.L. (2022). Autonomous vehicles digital twin: A practical paradigm for autonomous driving system development. Computer, 55(9): 26-34. https://doi.org/10.1109/MC.2022.3159500

[39] Sack, D. (2011). Governance failures in integrated transport policy–On the mismatch of 'co-opetition' in multi-level systems. German Policy Studies/Politikfeldanalyse, 7(2): 43.

[40] Pozoukidou, G. (2014). Land use transport interaction models: Application perspectives for the city of Thessaloniki. Spatium, (32): 7-14. https://doi.org/10.2298/SPAT1432007P