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Review Article

Systematic Literature Review on the Four-Step Travel Demand Model (FSM) and its Feasibility for Bi-nuclei Cities Context

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Abstract *- The Four-Step Travel Demand Model (FSM) has been extensively used in urban transportation planning to forecast travel demand and mobility patterns. However, its application to Bi-nuclei cities remains underexplored in systematic literature reviews. FSM, originally designed for monocentric urban structures, faces limitations in capturing interdependencies, congestion spillovers, and distinct travel behaviours between two dominant centres. Despite its widespread use, no studies have systematically reviewed FSM's feasibility for bi-nuclei cities, leaving a significant gap in understanding how FSM can be adapted for such urban settings. Therefore, this study conducts a Systematic literature review to evaluate FSMs and additionally check their feasibility in bi-nuclei cities, examining their methodologies, challenges, and required adaptations. The study systematically reviews 54 research articles, identifying how FSM has evolved from traditional transportation models to modern AI-enhanced forecasting techniques. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach was applied, and academic databases such as Dimensions were used for article selection. Key research contributions from 1954 to 2024 were analyzed through methodology, focusing on FSM's trip generation, trip distribution, mode choice, and traffic assignment methodologies. The study identified Regression Analysis, Gravity Models, Logit-Based Mode Choice, and Dynamic Traffic Assignment (DTA) as the most suitable FSM methods for bi-nuclei cities while highlighting challenges such as inter-nuclei travel complexities, congestion spillovers, and heterogeneous mode preferences. Software tools like CUBE, VISUM, VISSIM, AIMSUN, Trans CAD, MAT Sim, and Python-based models were evaluated for FSM's computational feasibility in bi-nuclei settings. The findings enhance urban mobility planning and FSM adaptability to complex structures.*

Keywords *- Four-Step Travel Demand Model (FSM), Bi-Nuclei cities, Urban transportation planning, Systematic Literature Review (SLR), Traffic assignment, Multi-modal transport systems.*

1. Introduction

Transportation planning models are considered an essential tool in the decision-making stages [1]. It could be depicted as mirroring the way individuals view the world and make movements, whether (passenger movement) or (freight transport). NMOs provide an overview of the problem, design possible solutions, and compare the effectiveness of different strategies to optimize the transport system in urban areas and enhance the quality of service [2].

The variety of travel demand models is classified into two main types: trip-based models and activity-based models according to the trip choice made. The purpose of each model is different: trip-based models are used to estimate the demand for travel through discrete trips, whereas activity-based models model all of the activities people engage in in a day, giving a fuller picture of travel behaviour [3].

The traditional Four-Step Model (FSM) is an example of trip-based transportation modeling. This model consists of four key stages: trip generation, trip distribution, mode choice, and route assignment, which together help to predict travel patterns within a given area based on socio-economic data and land use characteristics [4].

Extensively, FSM is used in urban transportation planning, despite the fact that there is very little research addressing its application in bi-nuclei cities. The various literature reviews show that FSM is developed for monolithic cities and may not effectively account for dual-core dynamics. So, this is the first systematic literature review, focusing on the feasibility of the four-step model (FSM) in dual-core urban systems, identifying methodological challenges and proposing adaptations that align with the unique spatial and behavioural dynamics of bi-nuclei cities.

1.1. History of Traditional FSM

Most decision-making processes depend on models as fundamental components; Maps can be considered the first examples of such models. Throughout history, the priests who modelled solar eclipse events maintained power within different early societies [5]. The United States led the creation of transport modeling fundamentals during the 1950s as part of the Detroit and Chicago Transportation Studies program. The modeling techniques appeared in the UK during the early 1960s, specifically for the London metropolis, and afterwards brought crucial theoretical advancements across both North American and European territories. The modeling techniques gained theoretical comprehension through economic concepts developed during the 1970s to validate their practical origins, whereas modern computational capabilities expanded their analytical capacity since the era of unprecedented computing power. The focus underwent substantial transformation along with these modifications. Research from the earliest phase focused mainly on capacity assessment because transportation demands from the motor car industry kept increasing. Transport assessment now focuses primarily on using pricing measures to limit road transport growth because of major environmental concerns that emerged during the past 50 years [6]. FSM is widely used in personal travel demand modeling, as it has been the basis of research in this area for many years. Table 1 below provides information about important contributions to the development of FSM, focusing on significant studies and important developments starting from the 1950s up to the most recent ones. It is clear that these studies have transformed the way FSM can be applied and understood in transportation modelling.

Table 1. Historical overview

Year	Citation	Work Done by Author
1954	[7]	The authors develop a link between travel and activities, beginning the theoretical framework.
1979	[8]	Manheim introduced the Transportation Systems Analysis (TSA) framework that helps examine FSM strengths and weaknesses.
1986	[9]	McNally and Recker contributed to the simulation of household travel/activity patterns.
1988	[10]	Florian et al. provided a two-dimensional framework to understand transportation planning models.
1997	[11]	Weiner's overview of urban transportation planning in the U.S. established FSM as part of large-scale projects.
1998	[12]	Martin and McGuckin developed techniques for travel estimation in urban planning, applying them to FSM.
2001	[13]	Ortuzar and Willumsen published Modelling Transport, which contributed to understanding FSM and its implications.
2007	[4]	McNally's updated overview of the FSM in the Handbook of Transport Modelling.

1.2. The Demand for a Systematic Literature Review

The interaction between land use and transport is considered one of the most tortured areas of urban transport and mobility studies, as mentioned by the researchers, and suggests the need for a systematic literature review in this field of study. Although many systematic review studies were applied to urban planning and transport modeling processes, there is still a notable research gap in identifying bi-nuclei cities.

Bi-nuclei cities, characterized by two dominant centers of economic and social activity, present unique mobility patterns, trip distributions, and transport infrastructure needs distinct from monocentric and polycentric urban structures. However, a review of existing literature reveals that most urban transport studies focus on traditional monocentric city models, with limited research explicitly addressing bi-nuclei urban formations in the case of FMS.

A systematic literature review is essential to identify gaps, synthesize findings, and propose new frameworks for studying the Four-Step Travel Demand Model (FSM) application in bi-nuclei cities. The lack of dedicated research on bi-nuclei cities highlights the need for a focused, evidence-based analysis that integrates urban land use, transport modeling, and multi-modal mobility solutions. Addressing this gap through a systematic review will support more sustainable and adaptive urban planning strategies for cities with dual-core development patterns.

In contrast to other broad-based reviews of the Four-Step Travel Demand Model (FSM), this review is devoted to reviewing its use in a less explored context of bi-nuclei urban settings. In a structured review of 54 research papers in the research article of the PRISMA framework, the paper will provide a narrow analysis of the strengths and weaknesses of FSM and provide a practical flexibility of the same in the context of dual-core cities.

2. Materials and Methods

The selected aspects of the study method are detailed in five sections beginning with PRISMA, followed by resources, then inclusion and Exclusion criteria, next to the SLR process, and finally, decision support falls to data abstraction and analyses.

2.1. Prisma

PRISMA is widely recognized as a key framework for conducting systematic reviews and meta-analyses. It guides authors in gathering essential research materials, helping them assess the quality and thoroughness of the review. The PRISMA framework utilizes a randomized evaluation process, establishing a standardized approach for literature reviews across various research fields [14]. The PRIMSA method serves environmental management domains well because the researchers established proper research questions that satisfy systematic literature review requirements. PRISMA serves as an approach for medical research. The PRIMSA approach allows the identification of inclusion and exclusion criteria at the same time throughout the whole process. PRISMA reviews the entire scientific literature database during specific time intervals to perform systematic keyword searches of relevant terms relating to the four-step model literature review. By using PRISMA, researchers in the future will find all essential issues to serve as future priorities for urban public transportation reviews.

2.2. Resources

Dimensions is a comprehensive research database and analytical platform developed by Digital Science**.** It is designed to provide researchers, institutions, and organizations with access to a vast range of scholarly information, including publications, citations, grants, clinical trials, patents, and datasets. Dimensions has become a valuable tool for conducting bibliometric analyses, tracking research trends, and discovering connections across various types of research outputs.

2.3. Approach for Conducting a Systematic Review for Selected Articles

2.3.1. Identification

The three essential phases defined the article selection process for systematic reviews. The initial step in creating a systematic literature review process is identification. The identification of relevant articles took place in this step. The search string was executed on the Dimension Database system in January 2025. The identification process of all relevant keywords is completed. The Dimension database yielded a large number of available papers, which reached 16149 articles.

- TITLE-AND ABSTRACT((“transportation planning” OR “urban transportation planning” OR “travel demand modelling” OR “four-step demand model” OR “travel model “OR “trip generation “OR “trip productions” OR “trip distribution” OR “mode choice” OR “modal split” OR “trip assignment model” OR “traffic assignment model” OR “travel demand estimation” OR “travel forecasting” OR “transportation systems analysis” OR “travel model validation” OR “travel model calibration”))

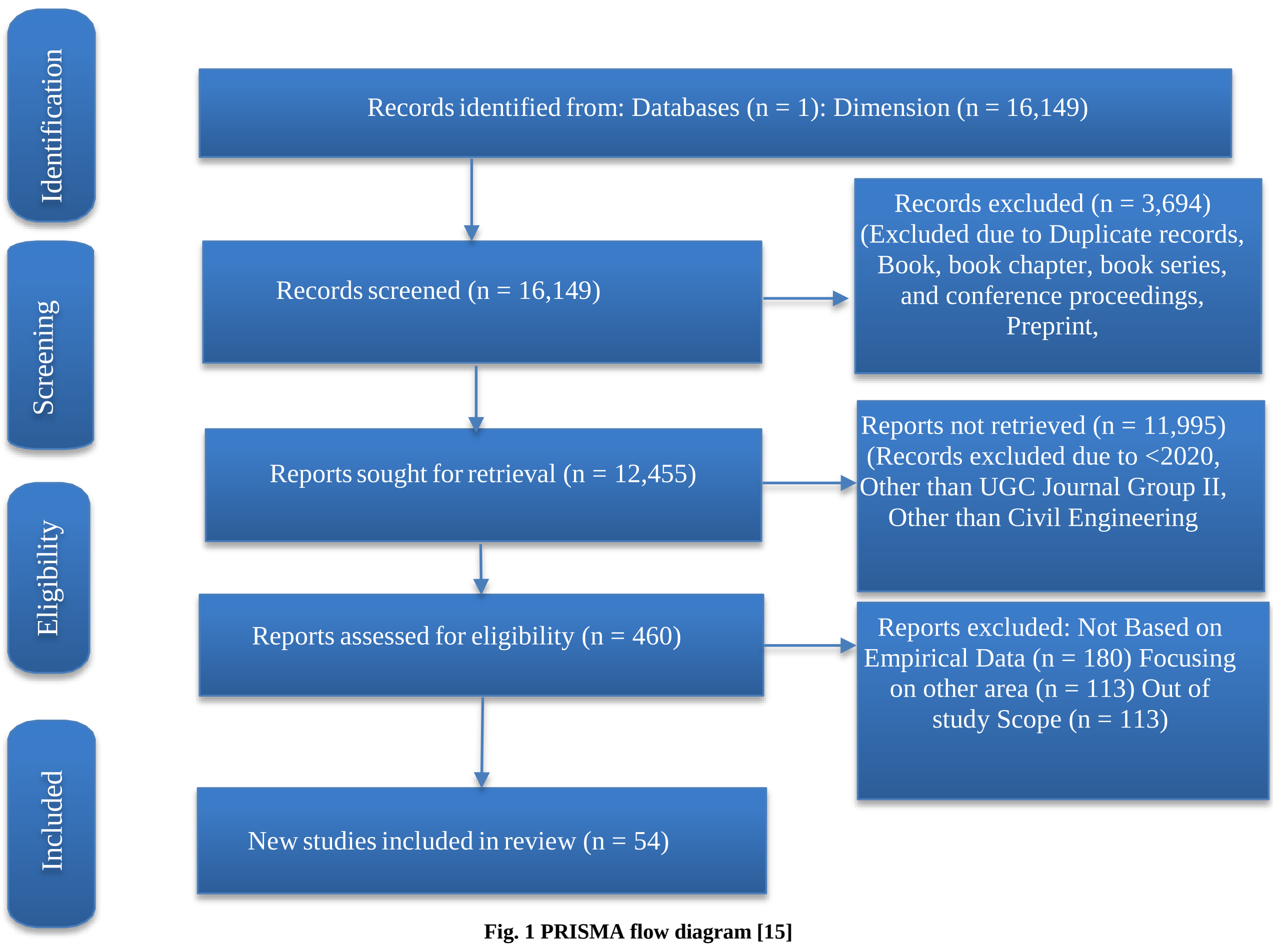

Fig. 1 PRISMA flow diagram [15]

Table 2. Inclusion and exclusion criteria

Criteria	Eligibility	Exclusion
Type of Literature	Journal (research articles)	book, book chapter, book series, conference proceedings, Preprint,
Language	English	Non-English
Time frame	2020 to 2024	<2020
Journal List	UGC Journal Group II	Other than UGC Journal Group II
Subject Area	Civil Engineering,	Other than Civil Engineering,

2.3.2. Screening

Data selection entered the second phase when researchers performed a screening operation. The study aims to research articles from journals because journals serve as key sources of empirical data. During this step, research articles in the form of books, book chapters, book series, conference proceedings, preprints, and monographs were omitted from the final pool of 12455 articles. Published research articles in English served as the main subject of examination during this study. The research focused on UGC Journal Group II and included only research articles from the five-year time period between 2020 and 2024. The selection of Civil engineering articles allowed greater opportunities to find research material suitable for the study. The research criteria resulted in the exclusion of 11995 research articles at this stage. Table 2 shows all details.

2.3.3. Eligibility

The third selection criterion was eligibility. The examination of research articles amounted to 460. The researchers verified the inclusion criteria compliance through detailed analyses of all selected articles, starting from their titles through abstracts and ending with the main content. The analysis continued with 54 research articles because they fulfilled the criteria of empirical data, urban public transportation, and an FSM focus. However, 406 articles were omitted at this point since they lacked empirical data and focused outside urban public transportation and FSM. This study presented a flow diagram, which can be observed in (See Figure 1).

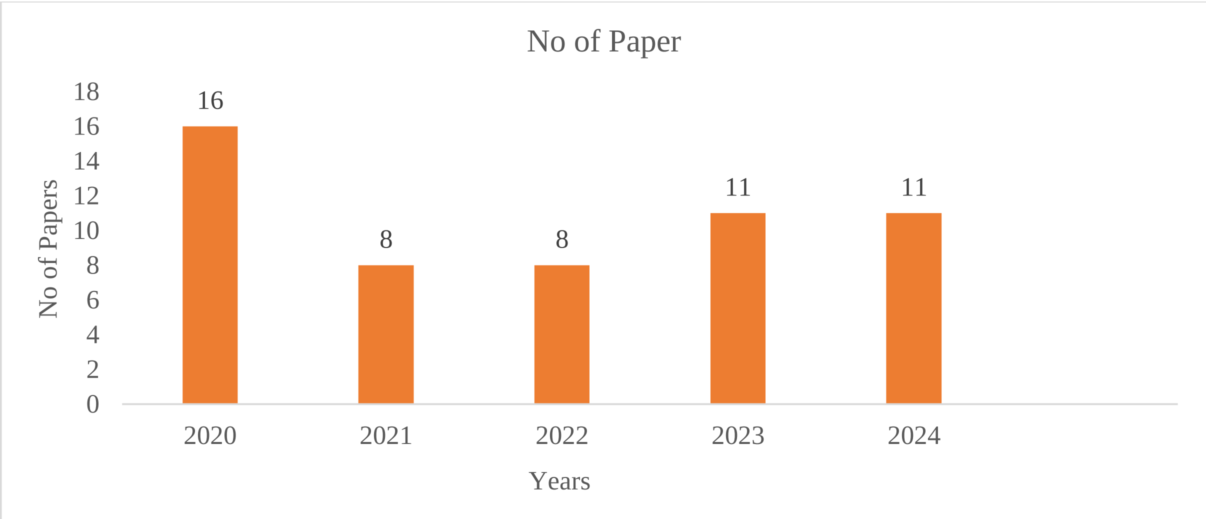

Fig. 2 No of papers (source- author)

3. Bibliometric Analysis

Bibliometric analysis is a powerful tool used to assess academic literature by quantifying key metrics such as publication trends, citation counts, and author impact. It helps identify emerging research topics, influential papers, and key authors, providing insights into the evolution of a field.

This analysis also highlights research gaps, evaluates journal quality, and maps academic collaborations, offering valuable information for researchers, institutions, and policymakers.

By leveraging citation patterns and publishing trends, bibliometric analysis aids in strategic decision-making, guiding future research directions, funding allocations, and publishing strategies.

The information suggests that developed and developing nations' research productivity and citation impact differ significantly. The United States and China lead far ahead when it comes to both documents and citations, with China at the top, having 179 documents and 1676 citations, and the United States at second with 110 documents and 1128 citations. These countries possess a high academic infrastructure, which will definitely result in great returns on investment with respect to research and innovation. Other developed countries like Australia (33 documents, 475 citations) and the United Kingdom (25 documents, 234 citations) also have noteworthy contributions, but their impact is much lower. On the other hand, developing countries like India, South Korea, and Iran tend to show lower numbers in the documents and citations, which may suggest lesser research resources combined with smaller academic outputs

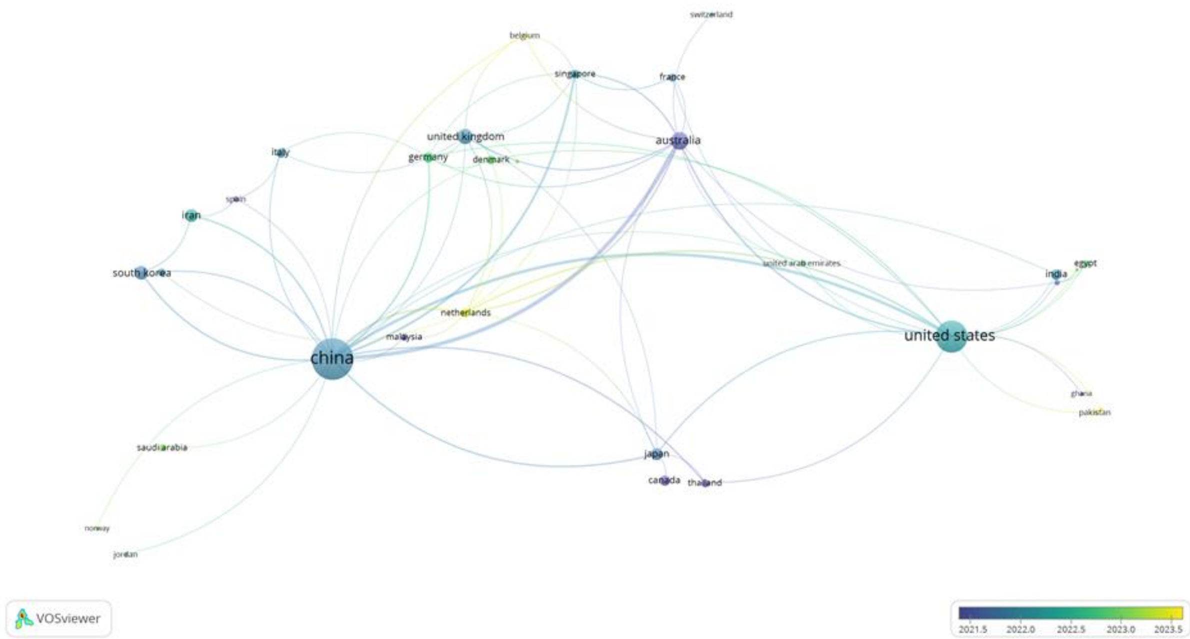

Fig. 3 Country-wise distribution (source- author) (VOS viewer used) (based on document count)

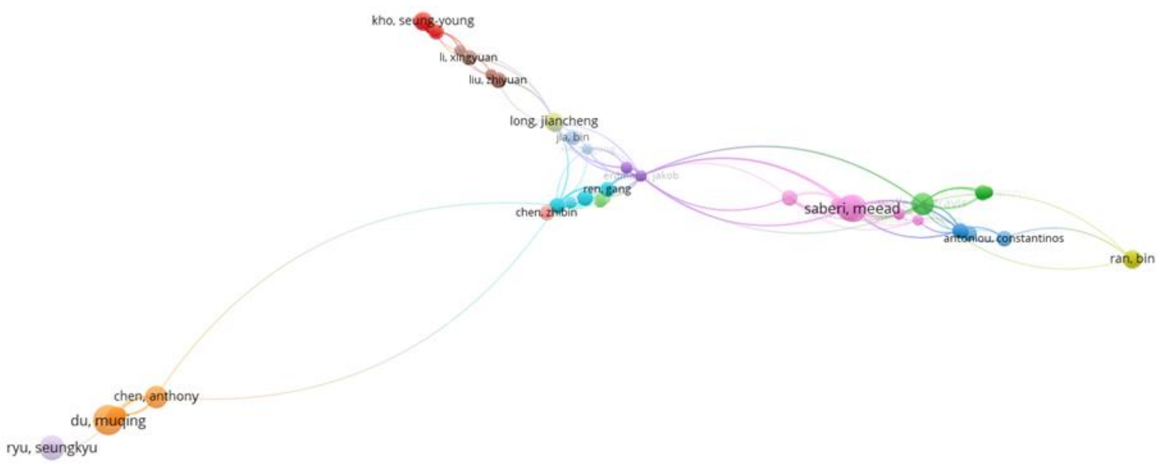

Fig. 4 Authors contributions (source- author) (VOS viewer used) (based on document count)

The Figure above shows the ranking of authors in terms of total documents published and citations earned. Du Muqing is on top in terms of documents published in 7 publications with 25 citations. In second place is Saberi Meead, who has 6 documents to his name but a much larger number of citations, which is 99. Other authors of interest are Chen Xiqun, who has 5 documents and 151 citations, and Gu Ziyuan, who has 5 documents and 92 citations. It can be inferred from the table that all authors had some level of contribution to research, which in turn was recognized by citations, signifying the impact of the authors' work in the field.

4. Extraction of Data and Advanced Analysis

A comprehensive integration review approach was conducted on 54 selected research papers focusing on the Four-Step Demand Model (FSM), a widely used framework in transport modeling. This structured review methodology analyzed and synthesized findings from various research designs. The approach allowed for the quantification of qualitative data and the qualitative interpretation of quantitative data from the research paper [16]. Ensuring a balanced and systematic understanding of FSM applications, limitations, and advancements. All selected research papers were systematically reviewed, and key themes and sub-themes were identified based on a thematic analysis. The first step involved data compilation, where the 54 designated research articles were examined in detail to extract statements and outputs directly addressing the research questions related to the FSM's accuracy, application, and adaptation. The second step involved categorizing and coding the research articles based on the type of data, research methodologies, and model variations used. This process transformed raw data into structured knowledge, identifying significant concepts, theoretical advancements, and practical applications [17, 18].

4.1. Main Findings

Research articles were classified according to the attributes they discussed for analysis purposes. The assessment of FSM benefited from the specific attributes that resulted from the previous study outputs. From this process, four main themes emerged, aligning with the Four-Step Demand Model's components:

- Trip Generation – Examining research on how socio-economic, demographic, and land-use factors impact travel demand predictions.
- Trip Distribution – Reviewing spatial interactions, gravity models, and regional connectivity in FSM applications.
- Mode Choice – Analyzing the factors influencing transportation mode selection, including economic, environmental, and policy considerations.
- Traffic Assignment – Evaluating research on traffic flow modeling, congestion mitigation, and multi-modal transport integration.

4.2. Approach to the Study

The study approach plays a crucial role in identifying previous research related to FSM. Within each main theme, sub-themes are created based on the Study area, Model Used, the Method of Data Collection, and Technological Details. In total, trip generation-7, Trip distribution-6, Model split-8, and Trip assignment-8 sub-themes were identified.

To ensure consistency and validity, the findings were cross-referenced with prior studies, and the entire data analysis process was recorded for transparency. Any inconsistencies in theme development were discussed and resolved through further synthesis and expert validation.

An expert review process was then conducted, where two domain specialists-one in transport modeling and urban mobility, and the other in quantitative forecasting techniques-assessed the relevance and rigor of the themes and sub-themes. Based on their feedback and recommendations, necessary adjustments were made to enhance clarity, coherence, and applicability to contemporary transport planning challenges.

Finally, adjustments were applied to refine and strengthen the developed themes and sub-themes, ensuring that the systematic review contributes valuable insights to the FSM study for Bi-Nuclei City. This structured approach provides a comprehensive and evidence-based analysis of the Four-Step Demand Model, supporting future research, policy formulation, and urban transport system optimization.

5. FSM Procedures

FSM is a widely used framework in transportation planning and demand forecasting. It is primarily used to estimate and predict travel behavior, demand, and traffic flow within a transportation system. This model helps planners and policymakers forecast the impact of transportation projects and policies on travel patterns, such as changes in road networks, land use, or transportation systems. Consists of four key steps. See Figure 5.

5.1. Trip Generation Step

The objective of this step is to define the number of trips that are produced or attracted to each zone on the transportation systems [19]. These generated trips could be classified according to trip purpose into three categories: See Figure 6.

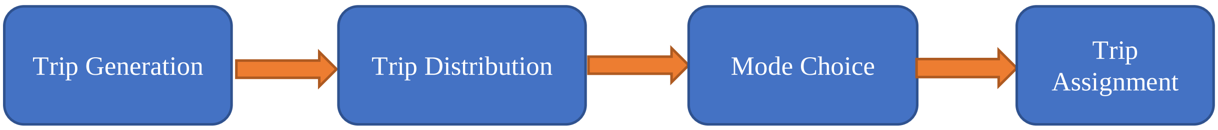

Fig. 5 Four steps

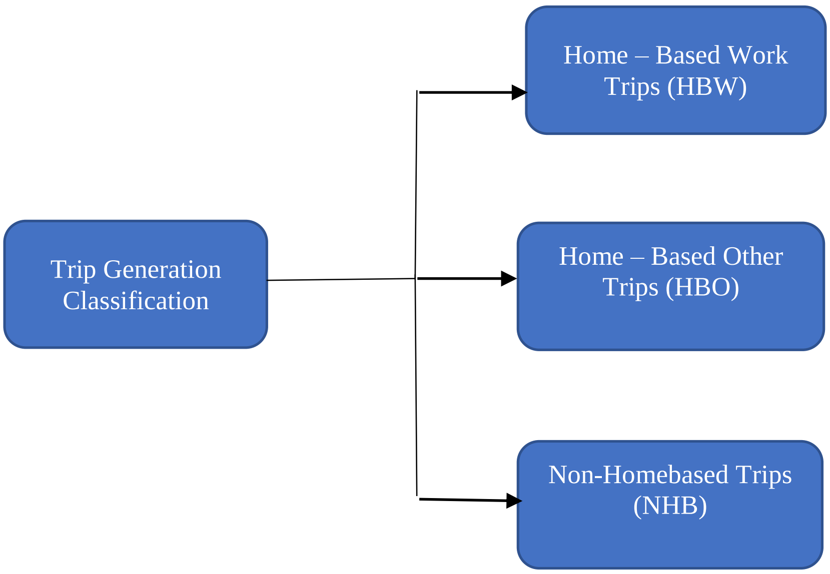

Fig. 6 Trip generation classification [20]

Trip generation is the first step in the Four-Step Model (FSM) of transportation planning, where the number of trips originating and ending in different zones is estimated. It plays a crucial role in understanding travel demand and forecasting transportation system requirements [21]. This step involves analyzing socio-economic and land-use characteristics to predict the total number of trips produced and attracted by various locations [22]. Trip generation studies rely on diverse data sources, including travel surveys, land-use data, and advanced data-driven techniques like cellular signals and social network-based datasets. Different modeling approaches, such as regression models, machine learning techniques, and spatial interaction methods, have been used to refine trip generation analysis. The accuracy of these models impacts subsequent stages of travel forecasting.

Table 3 show in the appendix below presents various trip generation studies, highlighting their methodologies, study areas, and key findings.

5.2. Trip Distribution Step

The objective of this step is to determine the trips between each pair of TAZs. Trip distribution is essential for understanding the human movements between TAZs in the study area [27]. The results of the trip distribution step could be classified into two types of outputs. The first type involves human movement between TAZs in the shape of a matrix or a table, the so-called "origin-destination" (O-D) matrix or table.

Table 4 show in the appendix provides an overview of various studies focused on origin-destination (OD) estimation across different transportation networks. It outlines key details such as study area, purpose, data collection methods, sample size, duration, and technical methodologies used for OD matrix estimation. The studies incorporate a range of approaches, including gravity models, Bayesian inference, deep learning, and real-time traffic monitoring to enhance trip distribution analysis and traffic management.

Table 5 describes trip distribution models by revealing their methods alongside necessary variables and modeling techniques, and concluding outcomes and restrictions. These forecasting models comprise traditional approaches, including gravity and growth-factor methods, and contemporary methods like random utility and activity-based models. The assessment evaluates different models for their suitability in trip pattern forecasting through the evaluation of computational demands and data needs alongside behavioral assumption validity.

5.3. Mode Choice

Mode choice is the third step in the FSM. Recently, many authors have studied the mode choice behavior of the travel makers as it is the most complex step in travel demand modelling [37-38]. The main objective of this step is to determine the number or percentage of zonal trips in terms of private or transit modes. Choosing travel mode is a complex process as it depends on many independent variables such as a person's income, car ownership, and many other factors. The essential concept of travel mode choice models is to understand the relationship between travellers' choice and the contributing factors, such as the socio-economic level and service level of modes. Table 6 shows in the appendix various studies across the world.

5.4. Trip Assignment Step

The final step in the traditional FSM is to determine the running routes that are estimated to be used and predict the number of vehicles in private transportation modes and passengers in transit transportation modes. The assignment process is the final output of the travel demand model (FSM). The assignment traffic results from loading travel demand trips between each TAZ on the network paths.

In essence, the congested network links have a major effect on travellers' route choice. For any link, it has been generally noticed that the speed decreases as the flow increases to the point at which the flow is equal to the capacity of the link. After this point, the flow and the speed decrease simultaneously, whilst travel time increases [68]. This relationship is represented in the "Volume Delay Function (VDF)" equation. VDF is used to express the travel time, or travel cost, on a network link as a function of the assigned volume on this link [69]. Usually, this function could be expressed as the result of multiplying the free flow time by the normalized congested function, as shown in Equation 1. The most famous VDF was developed by the Bureau of Public Roads (BPR) [70].

5.4.1. Trip Assignment Methods

Basically, the two main methods are Static Trip Assignment and Dynamic Trip Assignment [71]. STA assumes constant traffic conditions with fixed travel times, making it suitable for small, uncongested networks or early-stage planning, where computational simplicity is preferred. In contrast, DTA accounts for time-varying traffic flow, congestion, and incidents, providing more accurate, real-time traffic simulations for large, congested networks. DTA's ability to model traffic dynamics through feedback loops and its higher computational complexity make it ideal for real-time traffic management and congestion mitigation in urban environments [72]. Several trip assignment methods differ in the level of detail in dealing with route choice prediction. The most common methods are described in Table 7.

Table 8 shows in the appendix presents a detailed summary of 13 studies related to traffic assignment models applied in various contexts and regions. The studies cover a broad spectrum of methodologies, from Integrated Activity-Based Models (ABM) and Dynamic Traffic Assignment (DTA) to Stochastic Models and Game Theory-based approaches. Real-time traffic data and multi-source sensor data, together with emission constraints, form essential characteristics of these models, which apply to urban and expressway network systems.

Table 7. Various trip assessment methods

Method	Description	Use Case
All-or-Nothing (AON) Assignment	Assign all trips to the best route, with no congestion considered	Early-stage analysis, uncongested networks
Stochastic Assignment	Accounts for variability in travel costs or driver perceptions	Route choice under uncertainty, smaller-scale modeling
Trip Assignment with Congestion	Models congestion and traffic flow simultaneously	Urban traffic analysis, large-scale networks
Dynamic Traffic Assignment (DTA)	Models real-time changes and feedback in traffic flow	Real-time traffic management, peak-hour forecasting
User Equilibrium (UE)	Travellers choose routes minimizing personal travel time	Equilibrium-based modeling, urban transportation planning
System Optimal (SO)	Minimizes total system travel time for all users	System-wide optimization, supply-side management
Stochastic User Equilibrium (SUE)	Models route choices under uncertainty using probabilistic methods	Complex urban environments with varied traveller behavior

The systematic literature review of the Four-Step Travel Demand Model (FSM) provides an extensive review of its developmental history alongside its implementations and restrictions, thus demonstrating its vital role in urban transportation planning. The review indicates the increasing significance of enhanced modeling techniques, including activity-based models, together with dynamic traffic assignment and data-driven formulations for better FSM accuracy and current transportation needs management. The FSM has gained superior predictive forecasting capabilities through real-time data processing, autonomous vehicles, and multi-source sensors, leading to better scalability and universal urban applications. Future research needs to resolve the essential problems of computational cost, data demands, and environmental suitability for bi-nuclei cities despite their positive progress in FSM advancement. The review outcomes provide an essential understanding that guides future investigations about FSM deployment suitability within distinct bi-nuclei urban areas that need sophisticated travel demand forecasting techniques.

6. Bi-Nuclei Cities Context

Cities with two economic and social centers pose distinct management issues and opportunities to urban planners because they feature bi-nuclei configurations. Two-core cities differ from single-core cities because they need tailored approaches to run their network of roads and manage their built environment, along with human services. Because of the dual-core structure, the city experiences separate travel demands, different distributions of trips, and congestion patterns that make traditional planning methods harder to implement. Such circumstances create possibilities to enhance transportation frameworks to support vital connections between dual urban centers and develop eco-friendly convergence transport frameworks. Successfully tackling these difficult situations alongside these growing prospects needs creative strategies concerning urban design, multi-modal transportation systems, and policy establishment, specifically using FSM standards. Strategic solutions will create better transportation options and diminish traffic jams, which directly leads to higher life quality for inhabitants in cities designed with two main urban nuclei.

6.1. The Feasibility Check

To check the feasibility of applying the Four-Step Travel Demand Model (FSM) to a bi-nuclei cities context, you need to assess various factors that influence the model's applicability and effectiveness in capturing the unique dynamics of bi-nuclei cities. Here's a step-by-step guide to evaluate feasibility:

7 main steps in FSM (Four-Step Model) Assessment for Bi-Nuclei Cities: (See Figure 8)

- Assess Data Availability
- Evaluate Model Assumptions
- Examine Network Structure & Complexity
- Understand Socio-Economic & Behavioral Context
- Assess Model Calibration & Adjustments
- Evaluate Computational Feasibility
- Consult Stakeholders & Experts

In order to buttress this evaluation, a conceptual framework is advanced that makes the customary FSM fit the dual-core design of bi-nuclei cities. In this framework, two parallel trip generation centers (the two nuclei) are presented, the distribution of trips is adjusted to a dual-center gravity model, and separate mode choice modules that incorporate different traveller behaviors within each center are said to exist. The traffic assignment step is then assigned Dynamic Traffic Assignment (DTA) to account for congestion spill effects and inter-nucleus relationships. (See Figure 7). Many developments are providing smooth methods to solve node asymmetry, inter-nodal overcrowding, and congestion at many urban centers, like the Land Use Transport Interaction model (LUTI). They are useful in bi-nuclei and polycentric cities as their transport needs spatial inequality among urban cores. The proposed framework of the integration of dual-center gravity model and dynamic assignment techniques will offer enhanced realism to capture inter-nuclei travel resistance and asymmetric flows.

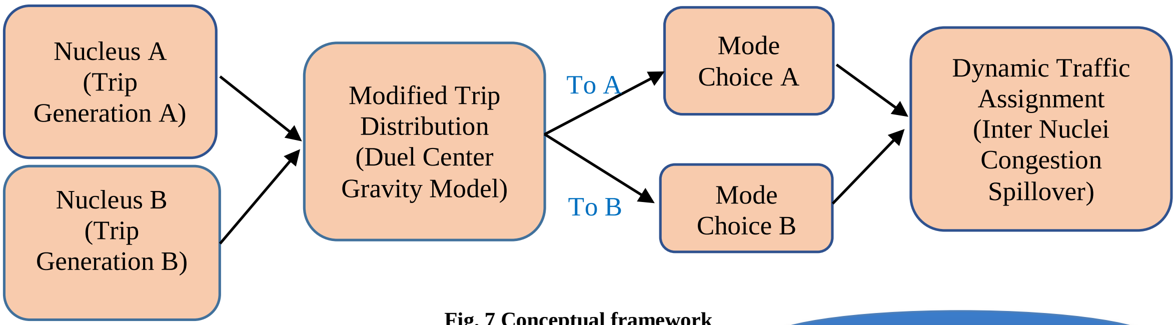

Fig. 7 Conceptual framework

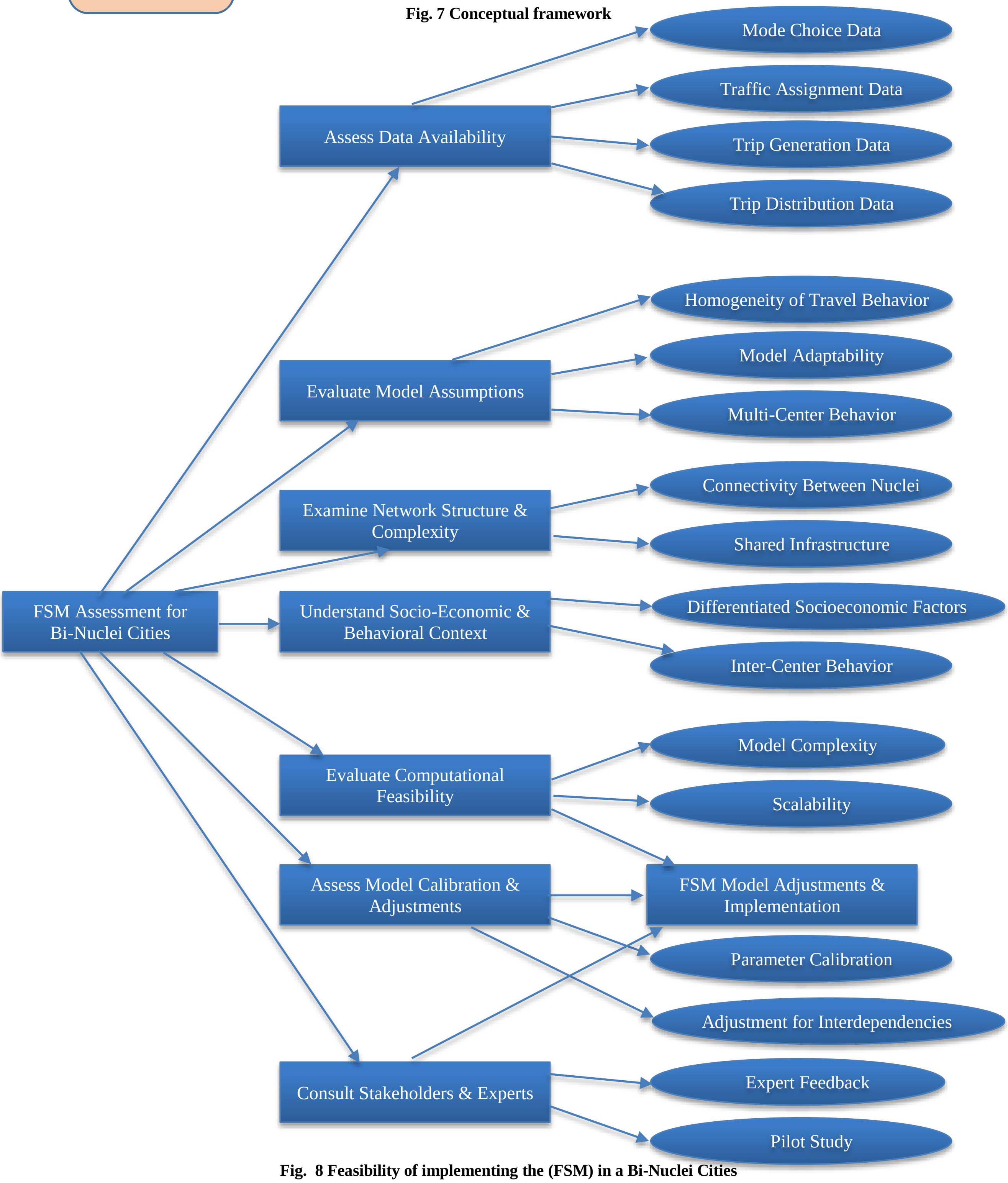

Fig. 8 Feasibility of implementing the (FSM) in a Bi-Nuclei Cities

This model provides a practical basis for adapting FSM to urban areas with two dominant centers, better addressing asymmetric travel patterns and multi-modal demands than traditional monocentric approaches. Furthermore, the proposed adaptation acknowledges several emerging modeling considerations. Inter-nodal elasticity may be represented through variable impedance factors between nuclei, enabling the model to reflect demand shifts due to congestion or policy changes. While not directly modeled, trip chaining is especially relevant in bi-nuclei systems where cross-core activities are frequent; future extensions could integrate activity-based modeling to address this. Similarly, trip generation adjustments informed by land-use dynamics and socio-economic patterns could enhance model responsiveness. Incorporating these elements would further strengthen the operational value of FSM for complex urban structures.

6.2. Case-Based Relevance of FSM in Indian Bi-Nuclei Cities

Some of the Indian metropolitan areas are bi-nuclei in nature, and the proposed FSM framework touches on the fundamental properties of these areas. An example is Hubballi Dharwad, which is under a single municipal corporation with the Hubballi Dharwad BRTS built in a 22.25-kilometer dedicated corridor that deals with inter-nodal flow of commuters. The practitioner application of this congestion system of transportation explains how the congestion spillover and dynamic demand between spatially distinct, yet functionally interdependent nodes must be modeled. The diversity of its land-use as well as shared infrastructure accentuates the significance of a customized FSM strategy that can take multi-core urban interactions. In Pune-Pimpri-Chinchwad, even though there are administrative disparities, the rate of sharp urban settlement, common job zones requires an interwoven modeling of travel needs to be required. Travel dynamics are also very complicated in the historic twinned cities of Hyderabad and Secunderabad, with common facilities such as the MMTS and the Hyderabad Metro. These examples, taken together, demonstrate the necessity to develop transportation planning models that would be able to take node asymmetry, inter-nodal elasticity, and multimodal behavior in Indian bi-nuclei cases into account, which serves to validate the viability and value of the proposed conceptual transformation of the FSM.

6.3. FSM Methods for Bi–Nuclei Cities

In the context of Bi-nuclei cities, the Four-Step Travel Demand Model (FSM) needs to be adapted to account for the presence of two dominant centres (nuclei) of activity within a single metropolitan area. Bi-nuclei cities often feature distinct travel patterns, interdependencies between centres, and specific transportation challenges. Here’s an analysis of which methods are the most suitable for each of the four steps of FSM when applied to Bi-nuclei cities. See table 9.

Table 9. Summary of FSM methods for Bi-Nuclei Cities

Step	Method	Why It’s a Good Fit for Bi-Nuclei Cities	Challenges
Trip Generation	Regression Analysis, Cross-Classification	Models trip generation based on heterogeneous characteristics between the two centers (e.g., population, employment, land use).	Inter-nuclei travel patterns must be carefully accounted for; differences in land use and economic activity between the nuclei make estimation more complex.
Trip Distribution	Dual Center Gravity Model, Customized Gravity Model	Accounts for intercity travel between the two nuclei, reflecting shared infrastructure and interdependencies.	Boundary effects can create highly variable travel demand; the model must accurately reflect congestion and travel resistance between the two centers.
Mode Choice	Logit Models, Nested Logit Models	Captures mode preferences and substitutions in travel behavior between the two centers.	Travel preferences may vary significantly between nuclei (e.g., one center relies on transit while the other favors private vehicles).
Traffic Assignment	Dynamic Traffic Assignment (DTA), User Equilibrium (UE)	Models time-varying traffic, congestion feedback, and interactions between the two centers.	Traffic spillover effects between nuclei must be accounted for; congestion in one center can impact travel patterns in the other, requiring advanced modeling techniques.

6.4. FSM Software Suitability for Bi-Nuclei Cities

To check the feasibility of applying the Four-Step Travel Demand Model (FSM) to bi-nuclei cities, you need software tools that can handle complex tasks such as data collection, statistical analysis, network modeling, and traffic simulation. Given the unique characteristics of bi-nuclei cities, the software should be capable of modeling intercity traffic flows, multi-centre interactions, and dynamic traffic conditions. Here's a list of the best-fit software tools for each step of FSM in the context of bi-nuclei cities and why they are suitable: See table 10.

Table 10. Summary of software tools for FSM Steps in Bi-Nuclei Cities

Step	Best Software	Why It's a Good Fit for Bi-Nuclei Cities	Challenges
Trip Generation	SPSS, R, Visum, Python (Pandas, Statsmodels)	Handles large datasets, demographic analysis, and models intercity travel.	Requires expertise in statistical modeling; Python and Visum need programming and configuration for bi-nuclei travel structures.
Trip Distribution	Trans CAD, VISUM, E-Travel, Python (NetworkX)	Models intercity travel flows, and handles Gravity Models and OD matrices.	High variability in trip distribution between nuclei requires accurate land use and network data.
Mode Choice	CUBE, VISUM, MATSim, R (mlogit, gmnl)	Suitable for multi-modal systems and heterogeneous traveller preferences.	Requires detailed traveler behavior data; MAT Sim and VISUM are computationally intensive for large networks.
Traffic Assignment	CUBE, VISUM, VISSIM, AIMSUN, DynusT	Models time-varying traffic flows and congestion in bi-nuclei cities.	Microsimulation tools (VISSIM, AIMSUN) demand high computational resources; DTA (DynusT) requires real-time data and calibration.

7. Conclusion

This systematic literature review (SLR) examined the historical development, applications, and challenges of the Four-Step Travel Demand Model (FSM), highlighting its evolution as a key tool in urban transportation planning. Multiple researchers provided substantial research findings for this study regarding the development of FSM as a trip-based travel demand modeling technique. The literature shows a knowledge gap regarding how FSM works in bi-nuclei cities since they possess two distinct urban cores with unique traffic flow patterns and dependencies, as well as congestion problems. Trips must follow specific modifications in all sections of the FSM, starting from generation through distribution to choice of modes and then traffic assignment. This study proposes the conceptual framework, the dual center Gravity Model, together with Logit-based mode choice models and Dynamic Traffic Assignment (DTA) as appropriate tools for Bi-nuclei cities. Yet, they face ongoing issues in inter-nuclei travel analysis, congestion effects, and diverse transportation preferences. The software tools SPSS, R, Python, Trans CAD, VISUM, MATSim, VISSIM, and AIMSUN provide FSM with computational capabilities, but they expect precise data along with advanced calibration and real-time simulation abilities. Peirce proposed during the feasibility assessment that FSM applications need adapted versions to become effective when applied to Bi-nuclei cities. The feasibility assessment concludes that FSM can be effectively applied to bi-nuclei cities with necessary adaptations. Future research should explore real-time traffic analysis, AI-driven forecasting, and multi-modal planning approaches to enhance FSM's adaptability for sustainable bi-nuclei urban development.

Author Contributions

A.S.M. conceived, designed, and performed a review of the literature; analyzed the data; wrote the paper; and A.V.S. and V.V.K. reviewed and proofread the manuscript. All authors have read and agreed to the published version of the manuscript.

References

[1] Amr M. Sakr et al., "An Integrated Approach of Travel Demand Modeling and Decision-Making Tools for the Assessment of Transportation Projects," *Journal of Transportation Engineering, Part A: Systems*, vol. 149, no. 10, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[2] Susan Powell, "Transportation Planning Models," *Journal of the Operational Research Society*, vol. 38, no. 12, pp. 1218-1219, 1987. [CrossRef] [Google Scholar] [Publisher Link]

[3] Joe Castiglione, Mark A. Bradley, and John Gliebe, *Activity-Based Travel Demand Models: A Primer*, Transportation Research Board, pp. 1-159, 2015. [Google Scholar] [Publisher Link]

[4] Michael G. McNally, *The Four Step Model*, Handbook of Transport Modelling, Emerald Group Publishing Limited vol. 1, pp. 35-53, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[5] David A. Hensher, and Kenneth John Button, *Handbook of Transport Modelling Article Information*, Emerald Group Publishing Limited, pp. 1-9, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[6] John Bates, *History of Demand Modelling*, Emerald Group Publishing Limited, pp. 11-34, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[7] Robert Buchanan Mitchell, and Chester Rapkin, *Urban Traffic: A Function of Land Use*, Columbia University Press, pp. 1-226, 1954. [Google Scholar] [Publisher Link]
[8] Marvin L. Manheim, *Fundamentals of Transportation Systems Analysis*, MIT Press, pp. 1-658, 1979. [Google Scholar] [Publisher Link]
[9] Michael Greyson McNally, *On the Formation of Household Travel/Activity Patterns: A Simulation Approach*, University of California, Irvine, pp. 1-388, 1986. [Google Scholar] [Publisher Link]
[10] Michael Florian, Marc Gaudry, and Christian Lardinois, "A Two-Dimensional Framework for the Understanding of Transportation Planning Models," *Transportation Research Part B: Methodological*, vol. 22, no. 6, pp. 411-419, 1988. [CrossRef] [Google Scholar] [Publisher Link]
[11] Edward Weiner, "*Urban Transportation Planning in the United States: An Historical Overview*," Report no. DOT-T-97-24, US Department of Transportation, Washington, DC, pp. 1-311, 1997. [Google Scholar] [Publisher Link]
[12] William A. Martin, and Nancy A. McGuckin, "*Travel Estimation Techniques for Urban Planning*," National Cooperative Highway Research Program, Transportion Research Board, Washington D.C, vol. 365, pp. 1-180, 1998. [Google Scholar] [Publisher Link]
[13] Juan de Dios Ortúzar, and Luis G. Willumsen, *Modelling Transport*, Wiley, pp. 1-499, 2001. [Google Scholar] [Publisher Link]
[14] David Moher et al., "Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement," *PLoS Medicine*, vol. 6, no. 7, pp. 1-8, 2009. [CrossRef] [Google Scholar] [Publisher Link]
[15] Neal R. Haddaway et al., "PRISMA2020: An R Package and Shiny App for Producing PRISMA 2020-Compliant Flow Diagrams, with Interactivity for Optimised Digital Transparency and Open Synthesis," *Campbell Systematic Reviews*, vol. 18, no. 2, pp. 1-12, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[16] Robin Whittemore, and Kathleen Knafl, "The Integrative Review: Updated Methodology," *Jounal of Advanced Nursing*, vol. 52, no. 5, pp. 546-553, 2005. [CrossRef] [Google Scholar] [Publisher Link]
[17] Margarete Sandelowski, "Qualitative Analysis: What it is and How to Begin," *Research in Nursing & Health*, vol. 18, no. 4, pp. 371-375, 1995. [CrossRef] [Google Scholar] [Publisher Link]
[18] Michael Quinn Patton, *Qualitative Research and Evaluation Methods*, 3rd ed., SAGE Publication, pp. 1-598, 2002. [Google Scholar] [Publisher Link]
[19] Zsolt Berki, and Janos Monigl, "Trip Generation and Distribution Modelling in Budapest," *Transportation Research Procedia*, vol. 27, pp. 172-179, 2017. [CrossRef] [Google Scholar] [Publisher Link]
[20] Houshmand Masoumi, "Home-Based Urban Commute and Non-Commute Trip Generation in Less-Studied Contexts: Evidence from Cairo, Istanbul, and Tehran," *Case Studies on Transport Policy*, vol. 10, no. 1, pp. 130-144, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[21] Akash Anand, and Varghese George, "Modeling Trip-Generation and Distribution Using Census, Partially Correct Household Data, and GIS," *Civil Engineering Journal*, vol. 8, no. 9, pp. 1936-1957, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[22] K. Isaac Takyi, "Trip Generation Analysis in a Developing Country Context," *Transportation Research Record*, no. 1285, pp. 9-21, 1990. [Google Scholar] [Publisher Link]
[23] Fan Yang et al., "A Data-Driven Approach to Trip Generation Modeling for Urban Residents and Non-local Travelers," *Sustainability*, vol. 12, no. 18, pp. 1-15, 2020. [CrossRef] [Google Scholar] [Publisher Link]
[24] Mykhailo Krystopchuk et al., "Exploring the Patterns of Resident Resettlement in Rural and Suburban Areas and Their Influence on the Passenger Trip Generation," *Periodica Polytechnica Transportation Engineering*, vol. 50, no. 2, pp. 191-204, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[25] Boon Hoe Goh, Choon Wah Yuen, and Chiu Chuen Onn, "Improvement of Trip Generation Rates for Mixed-Use Development in Klang Valley, Malaysia," *Scientific Reports*, vol. 13, pp. 1-9, 2023. [CrossRef] [Google Scholar] [Publisher Link]
[26] Abdul Basith Siddiqui et al., "Modelling Transit and Automobile TRIP-Generation Propensities of Post-Secondary Students in the Greater Toronto and Hamilton Area: A Cross-Sectional Study," *Canadian Journal of Civil Engineering*, vol. 50, no. 9, pp. 1-33, 2023. [CrossRef] [Google Scholar] [Publisher Link]
[27] Maxime Lenormand, Aleix Bassolas, and José J. Ramasco, "Systematic Comparison of Trip Distribution Laws and Models," *Journal of Transport Geography*, vol. 51, pp. 158-169, 2016. [CrossRef] [Google Scholar] [Publisher Link]
[28] Yiolanda Englezou, Stelios Timotheou, and Christos G. Panayiotou, "Dynamic Origin-Destination Matrix Estimation for Networks Operating Under Free-flow Conditions Using Macroscopic Flow Dynamics," *IFAC-PapersOnLine*, vol. 58, no. 10, pp. 213-218, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[29] Dongya Li, Wei Wang, and De Zhao, "Designing a Novel Two-Stage Fusion Framework to Predict Short-Term Origin–Destination Flow," *Journal of Transportation Engineering, Part A: Systems*, vol. 149, no. 5, 2023. [CrossRef] [Google Scholar] [Publisher Link]
[30] Shahriar Afandizadeh Zargari, Amirmasoud Memarnejad, and Hamid Mirzahossein, "Hourly Origin–Destination Matrix Estimation Using Intelligent Transportation Systems Data and Deep Learning," *Sensors*, vol. 21, no. 21, pp. 1-18, 2021. [CrossRef] [Google Scholar] [Publisher Link]
[31] Xavier Ros-Rocaa, Lídia Monterob, and Jaume Barceló, "Investigating the Quality of Spiess-Like and SPSA Approaches for Dynamic OD Matrix Estimation," *Transportmetrica A: Transport Science*, vol. 17, no. 3, pp. 235-257, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[32] A.S. Chairunnisa et al., "Modeling Origin Destination Matrix in the Inter-Island Cluster of North Liukang Using Gravity Model," *IOP Conference Series: Materials Science and Engineering: The 3rd EPI International Conference on Science and Engineering 2019 (EICSE2019)*, Sulawesi, Indonesia, vol. 875, pp. 1-11, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[33] M I Ramli et al., "An Estimation of Origin-Destination Matrices for a Public Transport Network in Makassar Using Macrosimulation Visum," *IOP Conference Series: Materials Science and Engineering: The 3rd EPI International Conference on Science and Engineering 2019 (EICSE2019)*, Sulawesi, Indonesia, vol. 875, pp. 1-8, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[34] Anselmo Ramalho Pitombeira-Neto, Carlos Felipe Grangeiro Loureiro, and Luis Eduardo Carvalho, "A Dynamic Hierarchical Bayesian Model for the Estimation of Day-to-Day Origin-Destination," *Networks and Spatial Economics*, vol. 20, pp. 499-527, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[35] Wenming Rao et al, "Investigating Impact of the Heterogeneity of Trajectory Data Distribution on Origin-Destination Estimation: A Spatial Statistics Approach," *IET Intelligent Transport System*, vol. 14, no. 10, pp. 1218-1227, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[36] Ennio Cascetta, Francesca Pagliara, and Andrea Papola, "Alternative Approaches to Trip Distribution Modelling: A Retrospective Review and Suggestions for Combining Different Approaches," *Papers in Regional Science*, vol. 86, no. 4, pp. 597-620, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[37] Anu Plavara Alex, Manju Vasudevan Saraswathy, and Kuncheria Palampoikayil Isaac, "Latent Variable Enriched Mode Choice Model for Work Activity in Multi Modal Condition Prevalent in India," *International Journal for Traffic and Transport Engineering*, vol. 6, no. 4, pp. 378-389, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[38] Ling Ding, and Ning Zhang, "A Travel Mode Choice Model Using Individual Grouping Based on Cluster Analysis," *Procedia Engineering*, vol. 137, pp. 786-795, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[39] Xu Yi, Kang Chen, and Zhongzhen Yang, "The Trend of the Structural Change of the City Taxi Market in China: A Modal Split Analysis in the Context of Different Market Access Rules," *Transportation Planning and Technology*, vol. 47, no. 4, pp. 598-621, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[40] I.M. Kariyana et al., "Urban Transportation Mode Choice Model in Bali," *Civil Engineering and Architecture*, vol. 12, no. 6, pp. 4031-4044, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[41] Thomas Kjær Rasmussen et al., "Local Detouredness: A New Phenomenon for Modelling Route Choice and Traffic Assignment," *Transportation Research Part B: Methodological*, vol. 190, pp. 1-31, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[42] Nitidetch Koohathongsumrit, Wasana Chankham, and Warapoj Meethom, "Multimodal Transport Route Selection: An Integrated Fuzzy Hierarchy Risk Assessment and Multiple Criteria Decision-Making Approach," *Transportation Research Interdisciplinary Perspectives*, vol. 28, pp. 1-14, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[43] David Leffler et al., "An Adaptive Route Choice Model for Integrated Fixed and Flexible Transit Systems," *Transportmetrica B: Transport Dynamics*, vol. 12, no. 1, pp. 1-28, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[44] Shin-Hyung Cho, Shin-Hyoung Park, and Sangho Choo, "Exploring the Travel Behavioral Differences for the Elderly Mobility on Public Transit," *Transportation Letters*, vol. 17, no. 1, pp. 61-71, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[45] Fan Ding et al., "A Hybrid Method for Intercity Transport Mode Identification Based on Mobility Features and Sequential Relations Mined from Cellular Signaling Data," *Computer-Aided Civil and Infrastructure Engineering*, vol. 39, no. 21, pp. 3206-3224, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[46] Jiankun Le, and Jing Teng, "Understanding Influencing Factors of Travel Mode Choice in Urban-Suburban Travel: A Case Study in Shanghai," *Urban Rail Transit*, vol. 9, pp. 127-146, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[47] Dewan Ashraful Parvez, "Joint Econometric Model Framework for Transportation Network Company Users' Trip Fare and Destination Choice Analysis," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2677, no. 7, pp. 545-557, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[48] Yu Gu, and Anthony Chen, "Modeling Mode Choice of Customized Bus Services with Loyalty Subscription Schemes in Multi-Modal Transportation Networks," *Transportation Research Part C: Emerging Technologies*, vol. 147, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[49] Lujin Zhao et al., "Using Conjoint Analysis to Incorporate Heterogeneous Preferences into Multimodal Transit Trip Simulations," *System Engineering*, vol. 26, no. 4, pp. 438-448, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[50] Zhan Zhao, and Yuebing Liang, "A Deep Inverse Reinforcement Learning Approach to Route Choice Modeling with Context-Dependent Rewards," *Transportation Research Part C: Emerging Technologies*, vol. 149, pp. 1-37, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[51] Yutong Shen, Yuelong Wu, and Baozhen Yao, "Research on Heterogeneous Traveler Travel Mode Choices with Differences under a Mixed Traffic Environment," *Sensors*, vol. 23, no. 13, pp. 1-13, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[52] Seungkyu Ryu, and Minki Kim, "Solving a Multi-Class Traffic Assignment Model with Mixed Modes," *Applied Science*, vol. 12, no. 7, pp. 1-12, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[53] N. Dheeraj Kumar et al., "Modeling Work Trip Mode Choice in Post-Metro Bengaluru City," *ECS Transactions*, vol. 107, no. 1, 2022. [Google Scholar] [Publisher Link]

[54] Khaled Assi et al., "Mode Choice Behavior Modeling: A Synergy by Hybrid Neural Network and Fuzzy Logic System," *Arabian Journal for Science and Engineering*, vol. 47, pp. 5255-5269, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[55] Chunyan Tang et al., "Modeling Limited-Stop Bus Corridor Services with Fare Payment Mode Choice and Trip Purpose Consideration," *Computational Intelligence and Neuroscience Computational Intelligence and Neuroscience*, vol. 2022, pp. 1-16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[56] Aleksander Purba, "Attitudes and Perceptions on Travel Mode Choice in an Emerging Urban Area of Indonesia: The Case of Southern Sumatra," *International Journal of GEOMATE*, vol. 23, no. 98, pp. 10-16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[57] Lingjuan Chen et al., "Construction of Commuters' Multi-Mode Choice Model Based on Public Transport Operation Data," *Sustainability*, vol. 14, no. 22, pp. 1-20, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[58] Seungkyu Ryu, "Mode Choice Change under Environmental Constraints in the Combined Modal Split and Traffic Assignment Model," *Sustainability*, vol. 13, no. 7, pp. 1-16, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[59] Xinyuan Chen et al., "Modeling a Distance-Based Preferential Fare Scheme for Park-and-Ride Services in a Multimodal Transport Network," *Sustainability*, vol. 13, no. 5, pp. 1-14, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[60] Shin-Hyung Cho, and Seung-Young Kho, "Exploring Route Choice Behaviours Accommodating Stochastic Choice Set Generations," *Journal of Advanced Transportation*, vol. 2021, pp. 1-14, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[61] Xiaowei Li et al., "Influence of Weather Conditions on the Intercity Travel Mode Choice: A Case of Xi'an," *Computational Intelligence and Neuroscience*, vol. 2021, pp. 1-15, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[62] Marek Drliciak et al., "Traffic Volumes as a Modal Split Parameter," *Sustainability*, vol. 12, no. 24, pp. 1-21, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[63] Xingang Li et al., "Modal Split and Commuting Patterns on a Bottleneck-Constrained Highway with Peak-Only Bus Lane," *Transportation Planning and Technology*, vol. 43, no. 8, pp. 821-850, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[64] Jianhui Wu et al., "Guidance Optimization of Travelers' Travel Mode Choice Based on Fuel Tax Rate and Bus Departure Quantity in Two-Mode Transportation System," *Journal of Advanced Transportation*, vol. 2020, pp. 1-10, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[65] Phattarasuda Witchayaphong et al., "Influential Factors Affecting Travelers' Mode Choice Behavior on Mass Transit in Bangkok, Thailand," *Sustainability*, vol. 12, no. 22, pp. 1-18, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[66] Bowen Hou, Shuzhi Zhao, and Huasheng Liu, "A Combined Modal Split and Traffic Assignment Model with Capacity Constraints for Siting Remote Park-and-Ride Facilities," *IEEE Access*, vol. 8, pp. 80502-80517, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[67] Kyoungok Kim, "Effects of Weather and Calendar Events on Mode-Choice Behaviors for Public Transportation," *Journal of Transportation Engineering, Part A: Systems*, vol. 146, no. 7, pp. 1-11, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[68] Sunduck Suh, Chang-Ho Park, and Tschangho John Kim, "A Highway Capacity Function in Korea: Measurement and Calibration," *Transportation Research Part A: General*, vol. 24, no. 3, pp. 177-186, 1990. [CrossRef] [Google Scholar] [Publisher Link]

[69] Heinz Spiess, "Technical Note- Conical Volume-Delay Functions," *Transportation Science*, vol. 24, no. 2, pp. 87-167, 1990. [CrossRef] [Google Scholar] [Publisher Link]

[70] United States. Bureau of Public Roads, *Traffic Assignment Manual: For Application with a Large, High Speed Computer*, U.S. Department of Commerce, Bureau of Public Roads, Office of Planning, Urban Planning Division, vol. 37, 1964. [Google Scholar] [Publisher Link]

[71] Andy H.F. Chow, "*Trip Assignment–A Literature Review*," California PATH, UC Berkeley, Report, pp. 1-24, 2007. [Google Scholar]

[72] Krishna Saw, B.K. Katti, and G. Joshi, "Literature Review of Traffic Assignment: Static and Dynamic," *International Journal of Transpotation Engineering*, vol. 2, no. 4, pp. 339-347, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[73] Yuhan Zhou, and Hani S. Mahmassani, "Faster Convergence of Integrated Activity-Based Models in Dynamic Multimodal Transit Assignment Using Macroscopic Road Congestion Estimation," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2678, no. 8, pp. 716-730, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[74] Ryuichi Tani, Teppei Kato, and Kenetsu Uchida, "Multiclass Traffic Assignment Model Considering Heterogeneous Stochastic Headways of Autonomous Vehicles and Human-Driven Vehicles," *International Journal of Intelligent Transportation Systems Research*, vol. 22, pp. 761-773, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[75] Ting Wang et al., "Multimodal Traffic Assignment Considering Heterogeneous Demand and Modular Operation of Shared Autonomous Vehicles," *Transportation Research Part C: Emerging Technologies*, vol. 169, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[76] Behzad Bamdad Mehrabaniet et al., "A Multiclass Simulation-Based Dynamic Traffic Assignment Model for Mixed Traffic Flow of Connected and Autonomous Vehicles and Human-Driven Vehicles," *Transportmetrica A: Transport Science*, vol. 21, no. 2, pp. 1-24, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[77] S. Zhao, L. Liu, and P. Zhao, "Traffic Assignment in Urban Transportation Network Problem with Emission Constraints in China: A Cooperative Game Theory," *Environmental Science and Pollution Research*, vol. 30, pp. 69274-69288, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[78] Seungkyu Ryu, Anthony Chen, and Songyot Kitthamkesorn, "A Two-Phase Gradient Projection Algorithm for Solving the Combined Modal Split and Traffic Assignment Problem with Nested Logit Function," *Journal of Advanced Transportation*, vol. 2021, pp. 1-18, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[79] Xing Zeng et al., “A Data-Driven Quasi-Dynamic Traffic Assignment Model Integrating Multi-Source Traffic Sensor Data on the Expressway Network,” *ISPRS International Jounal of Geo-Information*, vol. 10, no. 3, pp. 1-15, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[80] Haizheng Zhang et al., “Improving the Accuracy and Efficiency of Online Calibration for Simulation-Based Dynamic Traffic Assignment,” *Transportation Research Part C: Emerging Technologies*, vol. 128, pp. 1-26, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[81] Zainab Salam Al-Duhaidahawi et al., “Traffic Assignment of Al-Kufa City Using TransCAD,” *IOP Conference Series: Materials Science and Engineering: 3rd International Conference on Recent Innovations in Engineering (ICRIE 2020)*, Duhok, Iraqi, vol. 978, pp. 1-16, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[82] Mundher Seger, and Lajos Kisgyörgy, “Uncertainty Quantification of the Traffic Assignment Model,” *Periodica Polytechnica Civil Engineering*, vol. 64, no. 4, pp. 1181-1201, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[83] Junxiang Xu, Jingni Guo, and Jin Zhang, “Research on Traffic Assignment Model and Algorithm Based on Cumulative Prospect Theory under Uncertain Factors,” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2675, no. 4, pp. 116-134, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[84] Huijun Sun et al., “Day-to-Day Evolution Model Based on Dynamic Reference Point with Heterogeneous Travelers,” *Networks and Spatial Economics*, vol. 20, pp. 935-961, 2020. [CrossRef] [Google Scholar] [Publisher Link]

Appendix

Table 3. Critical analysis of trip generation studies

Citation	Area of Study	Method of Survey	Sample Size	Considered Variable	Modelling Approach	Findings	Limitations
[23]	Nanjing, China (38 Traffic Analysis Zones)	Data from cellular signals, location-based social networks (LBSN), POI data, and check-ins.	77,061 cellular signal base stations, 11,719 POIs	Number of POIs, number of users, number of check-ins, photos per POI, and socio-demographic factors.	OLS regression and Random Forest regression are used for feature selection.	Significant link between land use and trip generation, differences between urban residents and non-local travellers.	Relies on the availability of high-quality LBSN data, privacy issues, and limited data coverage.
[24]	Rural and suburban settlements	Computational geometry method (Voronoi diagrams, Delaunay triangulation) for spatial interaction.	Based on spatial data from rural settlements.	Population density, settlement size, and proximity to regional centre.	Regular model for population density distribution and resettlement patterns.	Identified significant spatial variability in population density and its impact on transport service demand.	Fixed assumptions in population distribution do not account for dynamic changes in settlement patterns.
[25]	Klang Valley, Malaysia (Mixed-use developments)	Traffic survey counts (vehicular and pedestrian) were conducted at four mixed-use development sites.	Data from four sites and an additional site for validation.	Gross Floor Area (GFA), number of parking spaces, dwelling units, and internal trip capture.	The regression-based method uses an internal trip capture adjustment factor.	A new adjustment factor (0.63) was established to reduce overestimated trip generation rates based on mixed land uses.	Relies on the accuracy of traffic counts and assumptions on internal trip capture, which may vary across developments.
[26]	Greater Toronto and Hamilton Area (GTHA)	Cross-sectional study using 2015 and 2019 data, including socio-demographic information and travel behaviour of post-secondary students.	Data from post-secondary students in the GTHA.	Commute distance, travel mode, socio-demographics (age, etc.).	Bivariate ordered probit (BOP) model for trip generation propensity prediction.	Commute distance decreases the likelihood of using transit and automobiles, and low-transit areas increase transit adoption.	Did not account for transit infrastructure and policy changes between 2015 and 2019.

Table 4. Critical analysis of trip distribution studies

Citation	Study Area	Objective	Tools Used	Number of Participants	Timeframe	Technical Specifications
[28]	Free-flow traffic network (general)	Proposes a methodology for dynamic OD estimation under free-flow conditions for efficient traffic management and network optimization.	Loop detectors, Traffic measurement sensors, and Simulation tools for real-time optimization.	Link traffic volume data from sensors	Real-time (dynamic estimation)	Uses a quadratic programming model for real-time OD estimation under free-flow conditions, integrating sensor data and flow dynamics.
[29]	Chongqing, China (Urban area)	Predicting short-term OD flows using a two-stage fusion framework combining attention-based spatio-temporal GCN and Kalman filter for OD flow prediction.	(AST-GCN), Modified Kalman filter (KF).	Traffic analysis zones (TAZ) data	Short-term predictions (real-time)	The two-stage fusion framework (TFF) consists of two phases: the initial phase employs AST-GCN for trip generation and attraction, while the subsequent phase uses a modified Kalman filter (KF) to predict OD flow. This approach emphasizes scalability for real-time applications.
[30]	Tehran, Iran (Metropolitan area)	Predicting hourly OD matrices for Tehran using ITS data and deep learning models.	GPS, ANPR cameras, smart fare cards, loop detectors, and traffic sensors are also available.	ITS data from various sources	Hourly predictions (real-time)	Uses deep learning models like Convolutional Neural Networks (CNN) to predict hourly OD matrices based on diverse ITS data (GPS, fare cards, ANPR, loop detectors). Evaluates performance based on RMSE and MAPE errors.

[31]	General traffic network	Exploring the dynamic OD matrix estimation by comparing Spiess-like and SPSA optimization approaches for improving traffic management.	Traffic data from measurement stations (traffic volume data).	Link flow data from network stations	Short-term analysis (time intervals)	A simulation-based approach is applied with SPSA (Simultaneous Perturbation Stochastic Approximation) and the Spiess method.
[32]	North Liukang, South Sulawesi (Inter-island network)	Modeling the OD matrix for both passenger and cargo trips using a gravity model to estimate trip flows between islands.	Gravity model, production constraint with exponential barrier function for estimating inter-island traffic.	Passenger and cargo data from the islands	Daily observations for passenger trips; cargo flow estimated	Uses a gravity model to estimate inter-island traffic flows. Applies an exponential barrier function for distance-based estimation.
[33]	Makassar, Indonesia (Public Transport Network)	OD matrices for public transport using macrosimulation	On-board observations, Frequency of service measurement.	Observations of public transport routes	Short-term (daily observation)	This study uses macrosimulation with the Visum software for modelling OD volumes,
[34]	General transportation network	Estimation of day-to-day OD flows using a dynamic hierarchical Bayesian model.	Traffic link volume data, Metropolis-within-Gibbs sampling algorithm for Bayesian inference.	Day-to-day link volume data	Day-to-day variation modeling	Dynamic Bayesian hierarchical model to estimate OD flows using a Metropolis-within-Gibbs algorithm. The model considers day-to-day variations and utilizes route assignment probabilities based on user-experienced costs.
[35]	Kunshan, China (Urban Road Network)	Exploring how variations in trajectory data distribution affect the accuracy of OD estimation, with an emphasis on spatial statistical methods.	GPS devices, Automatic License Plate Recognition (ALPR), traffic sensors, and a particle filter for trajectory reconstruction are also used.	Real-world trajectory data (vehicle paths)	Short-term (data sampling)	Uses the particle filter method to reconstruct incomplete vehicle trajectories and spatial statistics to analyze OD estimation accuracy impacted by heterogeneous trajectory data distributions.

Note* The second type of trip distribution output is to have movement representation on a production-attraction basis. There are many methods for the trip distribution steps. These approaches could be classified into two main categories: (a) Growth factor approaches, and (b) Gravity law approach [36].

Table 5. Trip distribution models

Model Type	Method Description	Variables Considered	Modeling Approach	Key Findings	Limitations
Growth-factor Methods	Distributes trips by expanding current trip distribution patterns with a growth factor. Uses a base trip matrix to forecast future trips.	Growth factor, existing trip matrix	Factor-based method, simple expansion	Simple to understand and apply, typically used for GDP forecasts.	Lack of explanatory theory, does not use origin-destination survey data directly.
Gravity Models	Uses a gravitational analogy for trip distribution, with trip flow being a function of zone size and distance between zones.	Population of origin and destination zones, distance between zones	Traditional gravity-based, proportional relationship	Widely used for general forecasting, it is easy to apply.	Assumes no individual behaviour, lacks behavioural theory, and does not consider perception attributes.
Intervening Opportunities Models	Introduces the concept that trip likelihood is influenced by the number of alternatives and intervening opportunities. Focuses on the rank order of destinations.	Distance, available opportunities, and the probability factor	Focuses on alternative availability, rank-order destination selection	Emphasizes alternatives and order of consideration, less dependent on exact distance.	Does not include transportation costs explicitly, and has limited use in practice.
Mixed Gravity-Opportunity Models	Combines the concepts of gravity and intervening opportunities, balancing distance and the number of competing opportunities.	Opportunities between origin and destination, general cost between zones	A hybrid model combining gravity and opportunities	Empirical evidence suggests this model yields better results than the basic gravity model.	Requires the calibration of more parameters; complexity increases with the number of zones.
Random Utility Models	Disaggregate models based on utility theory where destinations are chosen based on maximizing individual utility, incorporating both systematic and random utility components.	Socio-economic characteristics, travel cost, trip purpose, travel time	Utility-maximization, multinomial logit, nested logit	Allows for more flexibility by incorporating a wider range of attributes, including perceptions of destinations.	Requires extensive data for parameter estimation and is computationally intensive.

Activity-Based Models	Models travel behaviour based on activities that individuals plan, considering the entire set of activities in their daily agenda rather than modeling individual trips separately.	Activity scheduling, travel time, transportation mode, and socio-demographic factors	Activity-based approach, comprehensive analysis of trip chains	A better reflection of actual travel behaviour integrates various activities and trips into a single model.	Complex models with high computational requirements are still emerging for large-scale applications.
Mixed Logit Models	Extends the standard logit model by allowing for random variation in preferences across individuals, providing more flexibility in modeling individual travel choice.	Socio-economic characteristics, trip time, cost, and choice set alternatives	Mixed Logit model, random variability in preferences	The most promising discrete choice model for modeling transportation is particularly useful for varying individual preferences.	Requires large datasets, and can be difficult to interpret due to its complexity.
Dominance-Based Random Utility Models	Integrates the concept of dominance, where alternatives are ranked based on perceived benefits, using dominance degrees as perception attributes in random utility models.	Perception of alternatives, dominance attributes, travel costs	Random Utility Model with dominance-based attributes	Adds a new dimension by incorporating the dominance of alternatives into the decision-making process, improving model accuracy.	Needs a careful definition of dominance rules, which might be complex to apply in real-world scenarios.

Table 6. Critical analysis of mode choice studies

Study Title	Study Area	Mode Alternatives Analyzed	Model Type	Independent Variables	Data Collection Method	Sample Size	Key Findings	Limitations
[39]	Ningbo, China	Online Car-Hailing (OCH), Traditional Taxi (TT), Metro, Bus	Nested Logit Model	Fleet size, waiting time, service level, driver income	Observed travel data, surveys	City-level data from the Ningbo Transport Bureau	OCH significantly reduces TT market share due to better service quality and fleet expansion.	Market changes may influence long-term predictions.
[40]	Bali, Indonesia	Motorcycles, Light Vehicles, Public Transport	Structural Equation Model (SEM)	Age, income, travel distance, safety, punctuality, cost, comfort, security,	Survey data collection, SEM analysis	414 respondent s across Bali's districts	Motorcycles dominate due to cost efficiency, safety, and ease of use.	SEM-based results may have model estimation constraints.
[41]	Greater Copenhagen	Multiple route alternatives	Bounded Choice	Local detouredness, route attractiveness,	GPS route tracking,	Observed route	Local detouredness significantly	Requires calibration for different traffic

	Area, Denmark & UK	with detoured segments	Model with Local Detour Threshold (BCM-LDT)	stochastic user equilibrium	network analysis	choice data from 8009 trips	influences realistic traffic assignment and route choice behavior.	conditions and locations.
[42]	Bangkok, Thailand	Various multi-modal transport routes	Fuzzy hierarchy risk assessment & multiple criteria decision-making (MCDM)	Transportation cost, time, risk assessment, and decision-maker preferences	Survey-based risk assessment and hierarchical analysis	Multi-modal transport dataset from the Thailand-Singapore trade route	The proposed methodology effectively identifies the best multi-modal transport route.	Computational complexity increases with more alternatives and fuzzy risk analysis.
[43]	Stockholm, Sweden	Fixed-transit, flexible-transit, and active-mode alternatives	Utility-based transit route-choice model	Traveller adaptation, real-time route learning, flexibility in transit choices	Agent-based simulation framework	Simulated transit network in Stockholm	Model successfully captures dynamic route choices in mixed flexible and fixed transit systems.	Real-time adaptation modeling requires further refinement.
[44]	Seoul, South Korea	Metro, Bus, walking, taxi	Route choice behavior model (Multinomial Logit and Mixed Logit)	Travel time, willingness to pay, route attributes, elderly preferences	Stated preference survey, comparative behavioral analysis	Survey of 378 respondents (287 young adults, 91 elderly travellers)	Elderly travellers avoid complex routes and long transfer times, highlighting the need for convenient transfers.	Sample size limitations affect the generalizability of results.
[45]	Jiangsu, China	High-speed rail, air travel, and Bus	Hybrid classification model using mobility features and sequential data	Mobility features extracted from cellular data, sequential relations, and spatiotemporal dependencies	Cellular signaling data from mobile operators	Large-scale dataset from mobile network records	The hybrid model achieves 92% accuracy in identifying transport modes, improving travel behavior analysis for transportation planning.	Challenges with data granularity and spatial precision in cellular signals.
[46]	Shanghai, China	Urban rail transit, subway, Bus, shared bicycles	Discrete Choice Models (DCM) and	Travel time, cost, ‘last mile’ connectivity, service quality, socio-demographics	Stated and revealed preference surveys	Urban-suburban travellers in Shanghai	Suburban railways are crucial to changing urban-suburban travel	Challenges in quantifying ‘last mile’ connectivity, limited to Shanghai data

			machine learning				patterns; improved connectivity and pricing are key to higher public transport adoption.	
[47]	Chicago, U.S.	Transportation Network Companies (TNCs), ride-sharing modes	Joint econometric model	Trip attributes, destination attractiveness, origin and destination factors, socio-demographic, and weather attributes	TNC weekday trip data (January 2019 - December 2019), census-tract data	50 million trip records from Chicago, 44 million processed	Fare and destination choices are jointly determined by multiple factors; the joint model performs better than independent models.	The model assumes fixed destination choice based on TNC data, excluding temporal variations.
[48]	Hong Kong, China	Customized Bus (CB), private car, conventional Public Transit (PT)	Equilibrium mode choice model using Dogit and Nested Weibit models	Passenger loyalty, seat reservation, mode similarity and heterogeneity, loyalty subscription schemes	Survey-based data from CB services in multi-modal networks	Customized bus passengers in Hong Kong	Passenger loyalty to customized bus services significantly impacts mode choice behavior, particularly among long-term subscribers.	Passenger loyalty aspects may be oversimplified in the equilibrium modeling approach.
[49]	Washington, D.C., USA	Bus, Metro, Personal Car, Ride-hailing, Walking	Conjoint Analysis for Multi-modal Trip Simulations	Transfer type (intramodal, intermodal), time, walking, waiting, transfer penalties, socio-demographics	Conjoint survey data, commuter preferences, and multi-modal trip types	1651 commuters in Washington, D.C.	Commuters value the metro similarly to driving and prefer fewer transfers, with walking time penalized heavily.	Limited by the simplicity of mode transfer preferences and modeling assumptions.
[50]	Shanghai, China	Taxi GPS Data, Route Choice on Road Networks	Adversarial Inverse Reinforcement Learning for link-based route choice	State-action features, trip context, reinforcement learning for route preference estimation	Taxi GPS data, modeling of route choice behaviors	Taxi GPS dataset from Shanghai	Deep reinforcement learning models significantly outperform classical route choice models.	Challenges with context-dependent reward estimation and data sparsity in unseen destinations.
[51]	Beijing & Dalian, China	Autonomous Vehicles, Private Cars, Buses	Utility maximization model considering	Income, travel time, congestion, type of autonomous vehicles, VOTT (Value of Travel Time)	Survey-based, mixed traffic scenario analysis,	Data from heterogeneous traveller surveys in	Low-income travellers prefer buses, while high-income travellers prefer autonomous	Heterogeneity assumptions may oversimplify behavior, ignoring non-linear

			heterogeneous travellers		simulation models	Beijing and Dalian	vehicles with higher automation levels.	preferences across traveller groups.
[52]	Mixed Traffic Network, Various Urban Locations	Highways, Arterial roads, Transit networks with CAV and HV flows	Multi-Class Traffic Assignment with Mixed Modes	Proportion of CAVs, Mode Flow Interactions, Travel Time, Traffic Density	Theoretical modeling based on mixed traffic scenarios	Simulated Network and Real Transportation Data	The integration of mixed-mode flows (CAV and HV) enhances road capacity and reduces non-linear travel time.	Relies on theoretical models and simulated data rather than real-world observation.
[53]	Bengaluru City, India	Two-wheeler, Car, Bus, Metro, Company Bus	Multinomial Logit Model for Work Trip Mode	Age, Income, Vehicle Ownership, Travel Time, Travel Cost	Household interview survey, face-to-face interviews	675 respondents from all 198 wards in Bengaluru	Work trip mode choice is influenced by age, income, vehicle ownership, and service attributes like comfort and security.	Limited to Bengaluru data and does not account for external influences such as long-term policy changes.
[54]	Khobar-Dhahran Metropolitan, Saudi Arabia	Private car, walking	Hybrid Neural Network (ANN) & Fuzzy Logic System	Travel time, family income, school level, monthly income, travel distance, family size	Survey-based, self-administered questionnaires	1,484 valid surveys	SC-ANFIS performed better in predicting walking and passenger car modes for school students.	Relies on simulation data, limited to school-level choices
[55]	Dalian, China	Limited-stop bus, regular bus services	Optimization model for limited-stop services	Fare payment mode, passenger trip purpose, and bus dwell time	Simulation-based, passenger demand matrices	NA	The optimal service plan varies by demand and fare payment mode; the off-board payment mode saves time in high-demand corridors.	Assumptions regarding passenger behavior may oversimplify real-world complexities.
[56]	Southern Sumatra, Indonesia	AC bus, non-AC Bus, auto, motorcycle	State preference technique	Travel time, fare, headway, delay	Survey-based, stated preference technique	567 respondents	Non-AC bus users showed the highest shift potential to rail services; rail adoption varies by mode.	Limited to a single urban area in Indonesia; reliance on stated preferences.
[57]	Jimo District, Qingdao, China	Bus, subway, private car	Random parameter logit (RPL) model	Walking distance, travel time, cost, comfort, and waiting time	Public transport data (IC card,	26,591 commuters	Walking distance and comfort significantly influenced mode	Assumes perfect knowledge of travel characteristics; limited

					GPS, station data)		choice; the RPL model captures commuter preferences.	to public transport modes
[58]	Winnipeg, Canada	Private car, Public Transit	Combined Modal Split and Traffic Assignment (CMA) model	Environmental constraints, travel time, and CO emissions	Numerical simulations, real network	Small and real network	Environmental constraints led to a mode shift, improving efficiency by reducing CO emissions.	Limited to CO emission constraints and specific network examples
[59]	Urban transport network	Park-and-ride (P&R), Rail, Auto	Multi-modal transport network equilibrium model	Fare scheme, travel distance, park-and-ride system	Numerical simulations, network equilibrium models	NA	The distance-based fare scheme effectively encouraged P&R usage and improved transport network performance.	Limited to P&R services and the influence of fare schemes
[60]	Various locations	Various routes, urban and highway	Stochastic route choice model	Travel time, travel distance, cognitive travel process, reliability	Empirical data from RFID-based travel data collection	Real-world travel data from various origins and destination s	Introduces a new method for accommodating individual travellers' heterogeneity in route choice	Limited to routes with available RFID data, not considering non-RFID data
[61]	Xi'an, China	Aeroplane, High-speed rail (HSR), Conventional train, Express bus	Bayesian Multinomial Logit (BMNL) model	Temperature, wind, humidity, air quality, visibility, and rainfall	Survey-based, travel activity data matched with weather data	2028 valid survey responses	Weather significantly affects intercity travel choices, with weather parameters improving the model's prediction accuracy.	Limited to Xi'an; other regions might have different patterns.
[62]	Žilina and Kysuce regions, Slovakia	Private car, Public transport	Traffic flow and modal split analysis	Mobility surveys, travel time, and traffic volumes	households surveyed	6231 Survey of the House	Relies on simulation and survey-based assumptions, not real-time data	Further work could involve testing in other regions with real-time data integration
[63]	Bottleneck highway, unspecified	Private car, Bus (peak-only lane)	Bottleneck model with peak-only bus lane	Travel time, capacity constraints, and bus frequency	Simulation-based traffic modeling	NA	The peak-only bus lane improved modal shift and reduced travel costs	Limited to one scenario of the bus lane opening, not considering other

							for commuters; the effectiveness depends on bus dispatch frequency.	dynamic transportation policies
[64]	Two-mode transportatio n system	Car, Bus	Dual-mode network traffic flow evolution model	Fuel tax rate, bus departure quantity, travel time, operational cost	Numerical simulations, network modeling	NA	Fuel tax rate and bus departure frequency can significantly regulate car travel demand and improve bus service quality.	Limited to dual-mode system and specific assumptions; does not explore multi-modal integration.
[65]	Bangkok, Thailand	Private car, Mass transit	Binary logit model	Gender, age, income, vehicle ownership, travel cost, travel time	Revealed preference survey	4467 respondent s	Gender, income, and distance from the station significantly affect mode choice in Bangkok; private car usage is higher than mass transit.	Focuses only on socio-economic factors; does not consider long-term policy impacts
[66]	Suburban, China	Private car, Bus, Train	Bi-level optimization model with Nested-Logit user equilibrium (NL-UE)	Parking capacity, travel time, environmental constraints, and commuter preferences	Numerical simulations, traffic assignment models	NA	Optimized location and capacity of remote park-and-ride facilities can shift commuter preferences, reduce traffic, and improve social benefits.	Focuses on suburban areas and may not apply to highly urbanized settings
[67]	Seoul, South Korea	Subway, Bus	Generalized Linear Model (GLM)	Weather conditions, calendar events (holidays, weekends), and the built environment	Smart card data, 20 months	NA	Relies on smart card data, limited to one city’s public transit	Expanding to multiple cities, incorporating more environmental variables, could improve generalizability

Table 8. Critical analysis of traffic assignment studies

Study Title	Study Area	Model Type	Unique Features	Data Collection Method	Key Findings	Technological Innovation	Scalability and Applicability	Limitations
[73]	Greater Chicago Metropolitan Area	Integrated Activity-Based Model (ABM) and Dynamic Traffic Assignment (DTA)	Integrating congestion effects with activity-based demand models	Real-time traffic data, agent-based simulation	Faster convergence in achieving equilibrium when macroscopic road models are used	Integration of macroscopic congestion and demand-based models	Suitable for large-scale metropolitan areas with high computational resources	Requires significant computational power and real-time data infrastructure
[74]	Mixed Traffic Network	Stochastic Traffic Assignment Model	Incorporating headway randomness and mixed vehicle flow simulation	Log-normal distribution of headways, vehicle simulation	More realistic link capacities and travel time predictions with stochastic modeling	Hybrid model for mixed traffic (AVs and HVs)	Can be applied in AV-adoption cities; limited in cities with less AV infrastructure	Complex to model real-world mixed traffic with uncertain headways
[75]	Urban Area, China	Multi-modal, Multi-class Traffic Assignment Model	Modular operation of shared autonomous vehicles, heterogeneous traveller demands	Simulation of real-world multi-modal networks with SAVs	Modular SAVs optimize system efficiency, improve passenger flow, and reduce travel time	Dynamic SAV configurations and route adjustments	Highly scalable in cities with SAV infrastructure; adaptable for high-demand multi-modal areas	High complexity in routing SAVs, dependency on AV technology penetration
[76]	Multi-modal Traffic Flow	Simulation-based Dynamic Traffic Assignment Model	Considers mixed traffic of CAVs and HDVs, incorporates system-optimal behaviour for CAVs and user equilibrium for HDVs	Real-time traffic data, agent-based simulation	Simulation results indicate reduced total travel time as CAV penetration increases. Shows how CAVs' rerouting can improve overall traffic flow.	Open-source simulation framework for multi-class dynamic traffic assignment	Scalable to various cities with mixed vehicle fleets, adaptable for real-time applications	Requires significant computational resources, especially for large networks
[77]	Urban Transport Network	Cooperative Game Theory-based Traffic Assignment	Integrates vehicle emission constraints into traffic assignment using cooperative game theory to rank link importance	Simulation-based emission modeling	The cooperative game-based traffic assignment model outperforms traditional models by reducing emissions while maintaining system travel time within limits.	Incorporation of emission constraints in traffic assignment models	High applicability for cities with emission concerns, supports sustainable urban transport planning	Requires accurate emission data, limited by network-specific assumptions

[52]	South Korea Network	Multi-Class Traffic Assignment with Mixed Modes	Asymmetric interaction cost function for CAVs and HVs, utilizes the gradient projection (GP) algorithm for multi-class TAP	Simulation-based, network analysis	Increased percentage of CAVs significantly reduced travel time, with a non-linear reduction pattern. Convergence times decreased with more CAV road access.	Use of the GP algorithm to solve multi-class traffic assignment with mixed modes	Scalable to large transportation networks, effective for mixed-mode traffic scenarios	Requires further validation for real-world mixed-mode traffic conditions
[78]	Seoul, Korea	Gradient Projection Algorithm for Modal Split and Traffic Assignment	Two-phase GP algorithm solving the CMSTA problem with a nested logit (NL) model, hierarchical structure for mode choices	Traffic simulation data, computationa l models	The proposed GP algorithm outperforms MSA and Evan's algorithm, demonstrating faster convergence for large-scale multi-modal networks.	Improved traffic flow modeling for large-scale multi-modal networks.	Scalable to large transportation networks, adaptable for multi-modal systems	Computationally intensive for very large networks, and requires high precision in simulation data.
[79]	Hunan, China	Data-driven Quasi-Dynamic Traffic Assignment	Utilizes multi-source traffic sensor data (GPS, LPR, and toll records) for dynamic link cost estimation	GPS trajectory data, traffic sensor data (LPR, toll records)	The DQ-DTA model showed 6% higher accuracy than traditional STA models, improving traffic flow predictions with real-time data integration.	Integration of real-time traffic data for improved dynamic modeling	Applicable for large-scale expressway networks with high accuracy in flow prediction	High data requirements require real-time data integration, which can be costly.
[80]	Singapore	Online Calibration for Dynamic Traffic Assignment	Enhances EKF-based online calibration with state-augmentation and graph-colouring for better scalability	Real-time traffic data, simulation-based models	Improvements in prediction accuracy and computational efficiency, especially under congested network conditions.	Enhances the scalability of EKF-based calibration for large networks	Highly scalable for real-world DTA applications, effective for large cities	Requires complex computational resources, especially in dense traffic conditions.
[81]	Al-Kufa, Iraq	Traffic Assignment with Trans CAD and SUE model	GIS-based traffic assignment model for Al-Kufa city, focusing on major road traffic analysis	GIS data, traffic surveys, and field surveys	The study identified traffic congestion on roads with v/c > 1, highlighting road network deficiencies.	GIS and Trans CAD-based traffic flow simulation	Scalable for urban traffic studies in similar-sized cities	Limited data for smaller roads, dependency on field surveys

[82]	Hungary, General	Uncertainty Quantification (UQ) in Traffic Assignment	Focuses on the uncertainty of OD matrix inputs and their effect on traffic assignment outcomes	Statistical data, traffic flow data	Quantifying uncertainty in OD matrices led to more robust traffic flow predictions.	Inverse-UQ for robust traffic modeling	Applicable to large-scale urban traffic networks with uncertain input data	Requires high computational resources and precise data calibration
[83]	Sichuan-Tibet Region, China	Traffic Assignment based on Cumulative Prospect Theory (CPT)	Incorporates the uncertainty of supply and demand into the CPT-based traffic assignment model	Traffic flow data, environmenta l data	The CPT model outperformed traditional models by better handling uncertain demand and supply conditions.	Cumulative Prospect Theory for handling uncertainty in traffic assignments	Potential for use in regions prone to natural disasters or fluctuating demand	Limited to specific regions with uncertain supply and demand conditions
[84]	Beijing, China	Dynamic Reference Point Model with Heterogeneous Travellers	Incorporates dynamic reference points, captures route choice behaviour based on past experience and risk attitudes	Traffic flow simulation, historical traffic data	The model demonstrates how travellers' route choices evolve day-to-day based on dynamic reference points, considering gain and loss.	Incorporates behavioural economics (Prospect Theory) for route choices	Applicable to cities with heterogeneous traveller populations and dynamic traffic conditions	Assumes stable demand; complex modeling may limit real-world application in extremely variable environments