EQUILIBRIUM CONCEPTS AND DRIVER BEHAVIOR IN TRANSPORT NETWORK OPTIMIZATION: A SYSTEMATIC LITERATURE REVIEW

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Abstract

Road transport networks are collective systems whose condition depends on the independent route decisions of individual drivers. Each driver in a transport network seeks to minimize personal travel time or travel cost, and these self-interested route choices collectively result in a network state known as the user equilibrium, a condition conceptually consistent with the Nash equilibrium and often associated with congestion and inefficiency in transport networks. The daily growth in road traffic demand, the increase in motorization levels, and the growing need for sustainable transport network design necessitate new approaches to network optimization based on the equilibrium concept and a deeper understanding of driver behavior. This review paper employs a structured and comprehensive literature review and conceptual synthesis approach, using the recognized PRISMA method, to examine recent studies. The paper analyses equilibrium-based flow allocation in transportation, the behavioral aspects of route choice, and optimization strategies to assess equilibrium conditions and identify methods to improve collective transport network performance. This literature review examines how integrating an equilibrium-based approach with optimization strategies and transport policy measures can affect the efficiency and flow of transport networks. The paper highlights the importance of understanding equilibrium notions as a link between individual driver behavior and overall transport network performance. Literature review provides a growing body of knowledge on equilibrium concepts by systematically reviewing recent advancements and identifying emerging trends that will influence the future of transport network optimization. It identifies the key research gaps and potential avenues for future research directions and additional studies.

Keywords: nash equilibrium, transport network optimization, PRISMA, driver behavior, route choice

1 Introduction

It is important to understand the behavior of drivers in transport systems in order to analyze congestion, improve network performance, support optimization, and predict route choices. These choices shape traffic distribution and directly influence system efficiency, travel times, and overall network outcomes. A major part of this understanding comes from equilibrium theory, which provides a structured way to describe how travelers choose routes and how the network adjusts to these choices. These issues are becoming more relevant as traffic demand grows and the need for sustainable network design increases. Foundational work in this field began with Wardrop's principles, which determine a state in which no individual user can reduce their travel time by unilaterally changing their route [1]. Nash introduced the concept of non-cooperative equilibrium, defining a state in which each person's actions represent the best response to the actions chosen by others [2].

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Recent research has extended equilibrium concepts to more complex forms of driver and agent behavior, including dynamic route selection, multimodal decision-making, and interactions between human-driven and automated vehicles. These approaches apply equilibrium concepts to shared autonomous mobility and multimodal transport systems, showing that driver behavioral assumptions can noticeably influence network performance and optimization outcomes [3-5]. The literature shows significant variation in how equilibrium concepts are applied, how driver and agent behavior are represented, and how these models are incorporated into optimization frameworks. As a result, there is a limited systematic synthesis of the relationship between equilibrium concepts, behavioral modeling choices, and optimization objectives in transportation networks. This gap motivates the systematic literature review presented in this paper, in which RQ1 is defined as the primary research question, while RQ2 and RQ3 are formulated as the sub-questions:

- RQ1: How are equilibrium concepts applied to driver and agent behavior in transport network optimization problems?
- RQ2: How do equilibrium-based models represent driver and agent behavior in transport networks?
- RQ3: How are equilibrium-based behavior models used to formulate and solve transport network optimization problems?

2 Research methodology

The research process began by defining a structured strategy for searching relevant literature on equilibrium concepts, driver and agent behavior, and transport network optimization. For this paper, two major scientific databases were selected: Web of Science of Clarivate Analytics and ScienceDirect of Elsevier. Within the ScienceDirect database, the search was limited to leading transportation journals because they are well-recognized sources for research in the transportation field. These included Transportation Research Part A: Policy and Practice, Transportation Research Part B: Methodological, Transportation Research Part C: Emerging Technologies, Transportation Research Part E: Logistics and Transportation Review, Transport Policy, and Transportmetrica A: Transport Science. The research was conducted between September 2025 and January 2026. Only conference papers and peer-reviewed journal articles written in English published between 2020 and 2025 were considered. Non-scientific sources were excluded. Keyword combinations were used in the search: Nash equilibrium AND network AND transport, Equilibrium concept AND Road Transport, Nash equilibrium AND Road Traffic, Equilibrium concept AND driver behavior, Equilibrium concept AND optimization, Nash equilibrium AND route choice. It is important to note that the asterisk symbol (*) and double quotation marks (“”) were not used in the search. This systematic literature review, with the selection process shown in figure 1, uses the PRISMA method for screening and selecting papers. After collecting papers from the scientific databases, the records were checked for duplicate entries, and one duplicate paper was identified. The screening process then starts with three stages: title screening, abstract screening, and full-text review. Papers were excluded during screening if they were non-scientific (editorials, commentaries), out of scope, or unrelated to the research topic, or if they lacked methodological relevance and did not address the research question. After full-text review, papers were excluded if they did not apply an equilibrium concept or address driver or agent behavior in a transport network optimization context. The final dataset comprised 37 records and was classified into three main categories: the equilibrium concept used in the study, the type of behavior represented, and the type of optimization considered.

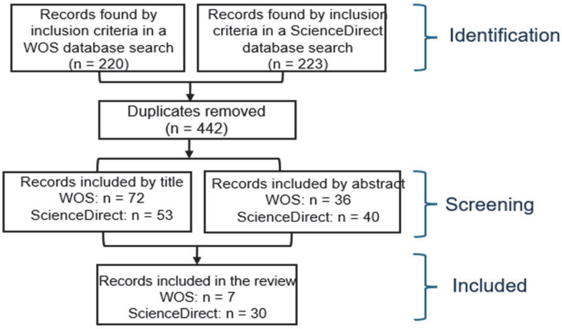

Figure 1 PRISMA flow diagram of the database search process

3 Results and synthesis

This chapter synthesizes the results based on a final dataset of 37 peer-reviewed papers, with their distribution by publication year and database is presented in figure 2. The analysis revealed that equilibrium concepts are applied in diverse ways across literature. To capture differences, papers are grouped into three categories: the equilibrium concepts adopted in transport network optimization, the representation of driver and agent behavior within equilibrium-based models, and the optimization approaches that build on equilibrium-based models.

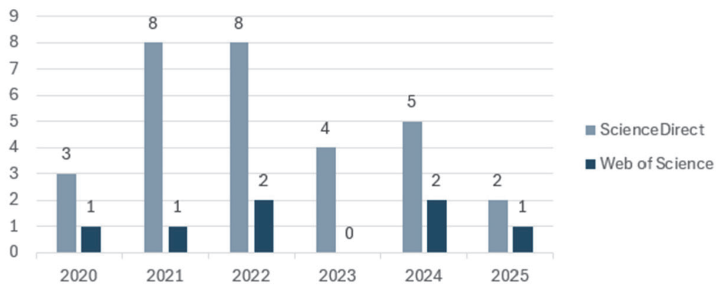

Figure 2 Distribution of selected studies by publication year and database

3.1 Equilibrium concepts in transport network optimization

Most of the reviewed literature represents driver behavior in transport networks using formulations based on the user equilibrium, making it the dominant modeling approach across the reviewed papers [6-10]. These studies rely on Wardrop's principles, assuming that users choose routes, departure times, and activity patterns to minimize their individual travel costs. Extensions of this framework allow traffic conditions, demand, and behavioral responses to evolve, leading to formulations based on dynamic user equilibrium. Some of the studies [11-13] extend user equilibrium formulations to more complex network settings, including shared autonomous vehicle systems, carpooling behavior, congestion-dependent transit route choice, multimodal networks, and integrated transport systems. For example, [6] formulate a model based on dynamic user equilibrium to analyze reservation-based shared autonomous vehicle services, while the authors in [14] apply equilibrium concepts of multimodal networks within a two-level framework to address the location problem of transit-oriented development. Authors in [5] develop a network equilibrium model for integrated shared mobility services, which shows how equilibrium flow distribution directly affects congestion patterns.

Authors in [15] investigate the convergence and stability of dynamic system-optimal traffic allocation using atomic users, highlighting the relationship between Nash equilibrium behavior and socially optimal flow patterns, in [16] introduce an average travel time equilibrium framework for autonomous vehicle control that implements optimal system flows over time and allows for the coexistence of system-optimal and user-equilibrium passengers over repeated planning cycles. Nash equilibrium is often used to represent competing driving strategies in transportation systems, showing that stable traffic patterns can emerge even when connected and autonomous vehicles act as selfish agents [17, 18]. Several studies [19-21] describe mixed-equilibrium concepts in regulated and heterogeneous transportation systems and examine the equilibrium of a shared network under mixed traffic comprising shared and individually routed autonomous vehicles. These contributions show how equilibrium concepts are increasingly used as flexible tools for modeling the capabilities and interactions among heterogeneous users, operators, and policy within transport networks [22]. Many user equilibrium formulations still rely on the behavioral assumption, which encourages the development of behaviorally richer equilibrium extensions discussed in subsequent sections. These findings are directly relevant to RQ1.

3.2 Driver and agent behavior in equilibrium-based models

Models based on user equilibrium represent the behavior of drivers and agents through cost-minimizing decisions, where it is assumed that users react rationally or boundedly rationally to the conditions of the transportation network. In user equilibrium-based formulations, drivers are typically modeled as self-interested decision makers who choose travel routes, departure times, and travel modes to minimize their individual costs, consistent with Wardrop’s assumptions and their dynamic extensions [6-8]. Some of the reviewed studies [8, 23, 24] include temporal adaptations and learning mechanisms that allow users to adjust their decisions in response to congestion over time and based on experience. In multimodal and integrated transport environments, different user groups often follow different equilibrium principles. For example, private drivers and car users may pursue user equilibrium–based behavior, while autonomous vehicle operators or public authorities pursue goals of system optimization and profit maximization [20, 25, 26]. This perspective is also supported by studies on shared electric vehicle systems, where equilibrium outcomes arise from strategic interactions between platform operators and power system operators in interconnected transportation and energy networks [27]. Studies also discuss game theory formulations that enrich behavioral representations by modeling drivers and agents as strategic decision makers whose actions depend on the expected reactions of other agents [28]. In these studies, behavior emerges from Nash, Stackelberg, or mixed equilibrium outcomes, and may involve cooperation or hierarchical coordination between drivers and network operators [29-32]. Drivers’ decisions are influenced by uncertainty, information, or probabilistic perceptions of travel costs. Such an approach allows behavior to vary adaptively across users and situations, especially under changing network conditions or network disruptions [33-35]. Driver behavior in mixed traffic environments is often modeled using game theoretic formulations that incorporate uncertainty cognition, allowing drivers to make lane change decisions based on perceived rather than perfectly known traffic conditions [36]. Overall, the reviewed literature represents driver and agent behavior through rational, adaptive, and strategic decision-making processes embedded within equilibrium frameworks. These findings directly answer RQ2 by explaining how equilibrium-based models conceptualize and operationalize behavioral assumptions in transportation networks.

3.3 Optimization approaches based on equilibrium behavior models

The literature shows that equilibrium-based behavioral models are often used as constraints or built-in mechanisms in transportation network optimization frameworks. The behavior of a driver or agent is first represented through an equilibrium state, which explains how traffic schedules, route choices, or departure times are formed. This principle is shown in two-level formulations where equilibrium behavior is a lower-level problem, and prices, system design, and decisions form a higher-level optimization problem [6, 14, 30]. Several studies [25, 27, 37, 38] use equilibrium-based models to optimize pricing schemes, subsidies, tolls, or incentive mechanisms to reduce congestion and improve network efficiency. In these studies, optimization processes often involve parking fees, toll levels, subsidies, or operational policies, while driver responses are captured through equilibrium travel choices. Optimization is also used in shared mobility and autonomous vehicle systems, where vehicle routing and assignment, service coordination, or reservation strategies are optimized depending on the equilibrium behavior of users and operators [6, 7, 16]. These studies show how equilibrium models with rational users and agents adjust their decisions in response to system-level control strategies. Several works incorporate equilibrium behavior into simulation and learning-based optimization frameworks. In such situations, equilibrium conditions guide adaptive processes and learning mechanisms that aim to improve network performance while preserving realistic behavioral responses [19, 34, 35]. In all approaches, equilibrium-based behavioral models are typically embedded in optimization frameworks, where competitive and cooperative equilibria are exploited to design traffic management strategies that improve system-level performance [39]. These results address RQ3 by showing that equilibrium models not only describe traffic states but also serve as fundamental components for solving traffic network optimization problems under realistic behavioral assumptions.

4 Conclusion

This paper presented a systematic literature review of equilibrium concepts and driver behavior modeling in transport network optimization based on a dataset of 37 peer-reviewed studies. The analysis confirms that equilibrium formulations constitute the core framework for representing driver and agent behavior and supporting network optimization. User equilibrium remains the dominant approach in modeling route choice and departure time decisions due to its analytical tractability and compatibility with optimization methods, while system-optimal and mixed equilibrium are primarily applied in strategic planning and policy-oriented contexts. The reviewed studies also reveal increasing efforts to incorporate behavioral realism through game-theoretic, learning-based, and stochastic extensions, particularly in research addressing autonomous vehicles and multimodal transport systems. However, these advanced approaches often entail significant computational complexity, limiting their application in large-scale or real-time optimization problems. Driver and agent behavior is most frequently embedded as a lower-level constraint within bi-level or multi-level optimization frameworks, enabling system operators to anticipate user responses when designing pricing, control, or incentive policies. The reviewed studies indicate a need for hybrid modeling approaches that reconcile behavioral fidelity with computational scalability and integrate empirical validation. Future research should therefore focus on developing equilibrium-based frameworks capable of representing complex behavioral processes while remaining applicable to real-world transportation networks. Ultimately, advancing transport network optimization will depend on integrating behavioral realism, computational efficiency, and empirical evidence, enabling more effective and adaptive management of increasingly complex transportation systems.

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