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Subway network optimization and passenger travel experience

Jingyu Wei

Haishan School, Laoshan District, Qingdao, Shandong Province

wjy17660235506@163.com

Abstract. This conference paper examines the significance of subway network optimization in relation to passenger travel experience. It begins with an introduction that highlights the importance of subway networks in urban transportation and establishes the objectives of network optimization. A comprehensive literature review explores previous research on subway network optimization and passenger travel experience, identifying strengths, limitations, and research gaps. The paper then explores various methods of subway network optimization, including network structure optimization, train scheduling optimization, and station layout optimization, providing explanations of their principles and application scenarios. The impact of these methods on passenger travel experience is discussed, considering evaluation metrics such as crowding level, punctuality, transfer efficiency, and comfort. A case study of the China Metro system is then presented to illustrate the implementation process of network optimization and an analysis of its impact on passenger travel experience using evaluation metrics. The findings emphasize the importance of subway network optimization and its potential to enhance passenger satisfaction, connectivity, and sustainable urban development. The conclusion connects with the paper thesis and main findings that underscore the significance of subway network optimization, proposing future research directions and exploring the relationship between optimization efforts and passenger travel experience. Therefore, the paper will help understand why subway network optimization and gives insights for enhancing passenger travel experience in urban subway systems.

Keywords: subway network optimization, network structure optimization, train scheduling optimization, and station layout optimization, crowding level, punctuality, transfer efficiency, and comfort.

1. Introduction

Subway networks play a vital role in the transportation infrastructure in many cities worldwide. They provide a reliable and effective way for people to travel and can help in reducing traffic congestion and air pollution. Recent subway inventions in countries like German, France, China, and Japan have seen an evolution of high-speed subway transportation that is electrified to decrease air pollution and that offers customer comfort while reducing congestion [1,2]. Moreover, the subway network has developed into a critical urban transportation aspect in many cities around the world. With the ever-increasing urbanization and population growth in cities globally, the subway network caters to the needs of a large number of commuters, and its demand continues to increase due to its efficiency and reliability [2]. While the demand for dependable and efficient transportation options continues to be a pressing issue

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worldwide, the optimization of subway networks has gained significant attention as a means to enhance the passenger travel experience and address the challenges associated with urban mobility.

1.1. Background and objectives of subway network optimization

As earlier established, subway networks significantly contribute to the transportation infrastructure. With the increased dependability on the subway, it is vital for network optimization to improve efficiency and offer a better travel experience for passengers. Notably, subway network optimization refers to the process of improving the design, operation, and management of subway systems to maximize their efficiency, capacity, and overall performance [3,4]. Optimization involves multiple aspects, including network design, train scheduling, station layout, and passenger flow management. Optimizing the subway networks creates a seamless and well-integrated transportation system that offers enhanced accessibility, reduced travel times, increased reliability, and improved passenger comfort [4]. As urban transportation continues to expand, there is a need for ongoing efforts to improve subway networks. Population density, urban sprawl, and evolving travel patterns are all factors that create significant challenges for subway systems to operate efficiently. These challenges can lead to overcrowding, delays, disruptions, and insufficient capacity [1]. To overcome these obstacles and provide sustainable and reliable transportation solutions, subway network optimization is necessary [1]. Therefore, the objectives of subway network optimization are twofold: to improve the operational efficiency and performance of the subway system and to enhance the passengers' overall travel experience. These objectives are closely intertwined, as an optimized subway network directly influences passenger satisfaction and the quality of their journey.

Network optimization involves strategic decision-making processes for optimal resource allocation, minimizing energy consumption, and maximizing system capacity [5]. This includes determining the best subway line layout, optimizing train schedules, and strategically locating stations to ensure efficient passenger flow and transfer connections [4]. Optimizing the network structure allows the subway system to handle higher passenger demand, reduce congestion, and enhance overall operational efficiency [4,5]. Simultaneously, passenger travel experience is a critical consideration in subway network optimization. A positive travel experience fosters passenger satisfaction, encourages public transport usage, and ultimately contributes to a more sustainable and livable urban environment. Factors that influence passenger travel experience include travel time, comfort, reliability, safety, and ease of transfer [6]. Ultimately, subway network optimization aims to minimize travel time, provide comfortable and convenient travel conditions, improve service reliability, and enhance passenger safety and security.

1.2. Correlation between subway network and passenger travel experience

It's clear that there's a direct correlation between the subway network and passenger travel experience. When a subway network is well-designed and efficiently operated, it can offer a lot of benefits to passengers that make their daily commutes more convenient and enjoyable [4]. By reducing travel times, optimizing train schedules, and providing reliable services, the subway network improves accessibility and connectivity, which allows passengers to get to their destinations more easily [4,7]. This increased connectivity has a positive impact on many aspects of daily life, including work productivity, leisure opportunities, and overall quality of life. Moreover, the subway network plays a crucial role in mitigating traffic congestion and reducing reliance on private vehicles, resulting in improved air quality and reduced carbon emissions [1]. The availability of a reliable and efficient subway network provides passengers with a viable alternative to private transportation, contributing to sustainable urban development and promoting environmentally friendly travel choices.

2. Literature review

2.1. Past research on subway network and passenger travel experience

Subway networks play a crucial role in urban transportation systems, providing efficient and sustainable means of commuting for millions of people worldwide. Accordingly, researchers have extensively explored the relationship between subway network optimization and passenger satisfaction, leading to a substantial body of literature in this field. Numerous studies have focused on different aspects of subway network optimization, including network design, train scheduling, station layout, and passenger flow management [4]. These studies have utilized various methodologies, including mathematical modelling, simulation techniques, and empirical analyses, to evaluate the effectiveness of different optimization strategies. For example, Wang et al. proposed a network optimization model that minimizes passenger travel time in Beijing by optimizing train schedules and frequency [8]. Their study demonstrated significant improvements in travel time and passenger satisfaction. Other studies have focused on applying advanced technologies and algorithms in subway network optimization. Zhuang et al. employed a genetic algorithm to optimize the layout and design of subway networks, considering factors such as station locations, line connectivity, and passenger demand [4]. Their research highlighted the potential of genetic algorithms in achieving optimal network configurations. There is also research on factors that influence passenger satisfaction and comfort. For instance, Wang et al. examined the impact of train interior design on passenger experience and proposed design recommendations to enhance comfort and accessibility [8].

2.2. Strengths, limitations, and research gaps

One of the strengths of previous studies is their emphasis on optimizing network structure to enhance passenger travel experience. Researchers have proposed innovative approaches to improve the connectivity and efficiency of subway lines, such as the integration of new technologies, the implementation of intelligent transportation systems, and the use of data-driven optimization algorithms [4, 6, 9]. These approaches have demonstrated promising results in terms of reducing travel times, minimizing transfer delays, and enhancing overall network performance.

Studies have also shown that optimizing train schedules is crucial. Researchers have made considerable progress in enhancing service reliability and decreasing waiting times for passengers by minimizing train headways, optimizing timetables, and taking into account factors such as passenger demand and system capacity [4, 6]. This directly benefits passengers by providing them with efficient and predictable travel conditions, leading to an improved travel experience.

The literature has also given much attention to optimizing station layouts. Researchers have explored ways to design and configure station layouts that can improve passenger flow, enable smooth transfers, and enhance accessibility [4]. The use of contemporary architectural and urban design concepts, like wayfinding techniques, intuitive signage, and passenger-centred amenities, has been identified as essential for creating a pleasant travel experience. Although previous studies have made valuable contributions to the field, they also have limitations and research gaps. One limitation is that many studies have solely focused on individual aspects of subway network optimization, disregarding the interconnected and comprehensive nature of the network [6]. To fully optimize the subway network, a holistic approach is necessary, taking into account the synergistic effects of different optimization strategies for network structure, train scheduling, and station layout [7].

Another limitation lies in the lack of long-term evaluation of optimization strategies and their sustained impact on the passenger travel experience. Most studies have predominantly focused on short-term effects, such as immediate improvements in travel times or reduction in delays [7]. However, it is essential to understand the long-term implications of these optimization strategies, including the potential for increased passenger demand, changing travel patterns, and evolving urban dynamics.

Furthermore, the integration of emerging technologies, such as smart mobility solutions, real-time passenger information systems, and predictive analytics, remains an underexplored area. These technologies have the potential to revolutionize subway network optimization and significantly enhance the passenger travel experience [4, 6, 12]. Future studies should explore the implementation and evaluation of these technologies to further improve the efficiency and effectiveness of subway networks.

In order to address these research gaps, future studies should consider taking interdisciplinary approaches. Collaboration between transportation engineers, urban planners, social scientists, and data analysts can provide a more comprehensive understanding of the complex dynamics between subway network optimization and passenger travel experience. Moreover, such collaborations can lead to innovation of solutions that take into account technical aspects and social and psychological factors influencing passenger satisfaction.

3. Subway network optimization methods

Subway network optimization employs different methods and strategies to enhance network efficiency, reduce travel times, and improve the passenger travel experience. Three common methods are used in subway network optimization: network structure optimization, train scheduling optimization, and station layout optimization [5, 11]. These optimization methods directly impact key factors such as travel time, convenience, reliability, and comfort, leading to improved passenger satisfaction.

Network structure optimization involves analyzing and modifying subway lines' physical layout and connectivity to enhance efficiency and capacity [11, 12]. This includes reducing line duplication, optimizing route configurations, and ensuring balanced line loads [5]. Improving the network structure helps the subway systems achieve better connectivity, reduce transfer distances, and minimize passenger travel times [6, 11]. Furthermore, network structure optimization can be applied to expanding existing networks or planning new lines in rapidly growing urban areas.

Train scheduling optimization aims to improve the travel experience for passengers by minimizing travel times, waiting intervals, and increasing service reliability [9, 11]. This is achieved by creating optimal timetables and determining train frequencies based on factors such as passenger demand, peak-hour variations, and system capacity [9]. When optimizing train schedules, it is important to reduce headways, maintain even train distribution, and coordinate transfers between lines [7,9]. Effective train scheduling optimization provides passengers with more frequent and predictable services, reduces crowding, and minimizes station waiting times.

Station layout optimization focuses on designing and configuring stations to maximize passenger flow, accessibility, and comfort [7, 11, 12]. Factors considered in this method include platform capacity, passenger circulation patterns, and transfer efficiency. Principles guiding station layout optimization include efficient platform design, clear signage, intuitive wayfinding systems, and appropriate allocation of passenger amenities [3, 13]. Well-designed station layouts ensure smooth passenger movements, minimize congestion, and provide convenient transfer opportunities, enhancing the overall travel experience.

4. Evaluation metrics for passenger travel experience

To assess the quality of passenger travel experience in subway networks, various metrics have been proposed. These metrics provide quantitative and qualitative insights into different aspects of the travel experience. Commonly used evaluation metrics include crowding level, punctuality, transfer efficiency, and comfort [2,3,13]. Crowding level is a crucial metric that measures the density of passengers within subway systems [13]. It indicates the level of congestion and overcrowding experienced by passengers during their journeys [5,13]. High crowding levels can negatively impact passenger comfort and overall travel experience. Measurements can be based on passenger counts, occupancy rates, or spatial analysis techniques.

Punctuality measures the adherence of subway services to their scheduled timetables [10, 13]. It reflects the reliability of train operations and the occurrence of delays or deviations. Punctuality is critical to passenger satisfaction, as delays can lead to missed connections and increased waiting times [7]. Measurements can involve comparing actual arrival and departure times with scheduled times and calculating delay durations.

The transfer efficiency metric assesses the ease and convenience of transferring between different subway lines or modes of transportation within a transit system [7, 13]. Efficient transfers contribute to reduced travel times and improved overall experience [10]. Metrics consider factors such as walking distances, wayfinding systems, signage clarity, and connection times. Finally, the comfort metric evaluates the physical and psychological well-being of passengers during subway journeys [1, 7, 13]. This metric is subjective and includes factors like seating availability, air quality, noise levels, cleanliness, and overall satisfaction. Assessment methods include passenger surveys, interviews, and objective measurements such as noise level and air quality monitoring [12].

5. Case study of subway network optimization

To demonstrate the practical application of optimizing subway networks and its effects on passenger experience, we will examine the China Metro system. This subway network is renowned globally for its size and complexity. The implementation process of network optimization in the China Metro system involved a comprehensive approach to address urbanization challenges and meet the growing transportation demand [14,15]. It began with an extensive analysis of passenger demand, travel patterns, and system performance [14]. To optimize the network structure, the system underwent significant expansion. New subway lines were added and existing lines extended strategically to connect key residential, commercial, and transportation hubs [14]. This expansion improved connectivity, reduced travel times, and provided better access to various destinations within the city [6, 14,15]. Furthermore, the metro system focused on train scheduling optimization to accommodate passenger demand and enhance service reliability [6]. Advanced algorithms were employed to optimize train frequencies, minimize delays, and reduce waiting times [14]. The revised schedules aimed to facilitate efficient connections at transfer stations, further enhancing the travel experience. The impact of these optimizations on the passenger travel experiences was assessed using the previously reviewed evaluation metrics like punctuality, crowding level, comfort, and transfer efficiency.

Quantitative analysis revealed a noticeable reduction in crowding levels. The expansion efforts and increased capacity eased congestion during peak hours, resulting in improved passenger comfort and reduced travel stress [2, 6]. Punctuality analysis indicated enhanced service reliability, with fewer delays and deviations from the timetable. The optimized train schedules, tailored to handle passenger demand and minimize disruptions, led to increase on-time arrivals and departures [2]. Additionally, transfer efficiency analysis demonstrated improved ease and convenience when transferring between different subway lines [2,15]. The optimization measures minimized transfer distances, and improved wayfinding systems, streamlined transfers. Passengers experienced shorter transfer times, enhancing journey efficiency and satisfaction.

The qualitative analysis focused on comfort, and it revealed positive feedback from passengers. The China Metro system invested in station modernization [8, 14], including the addition of seating areas, improved lighting, and better ventilation systems [15]. Cleaner and quieter environments enhanced passenger comfort, contributing to a more pleasant travel experience [6,8].

China’s metro system network optimization improved the passenger travel experience [6]. The expansion of the network, optimized train scheduling, and improved station amenities resulted in reduced crowding, increased punctuality, enhanced transfer efficiency, and improved comfort. These enhancements elevated passenger satisfaction levels and solidified the China Metro system's reputation as a reliable and efficient transportation option.

6. Conclusion

The research conducted on subway network optimization and passenger travel experiences reveals that optimizing subway network structure, train scheduling, and station layout can significantly enhance efficiency, reduce travel times, improve punctuality, enhance transfer efficiency, and increase passenger comfort [5, 13]. The case study of the China Metro system serves as a practical example, demonstrating how these optimization efforts resulted in reduced crowding, increased reliability, smoother transfers, and improved overall comfort for passengers.

The importance of subway network optimization in improving passenger travel experience cannot be underestimated [13]. A well-designed and efficiently operated subway network offers numerous advantages, including shorter travel times, better connectivity, increased predictability, improved comfort, and a viable alternative to private transportation [5]. These improvements contribute to higher passenger satisfaction, increased usage of public transport, and the creation of liveable and sustainable urban environments. Nevertheless, future research should consider adopting a more comprehensive approach to subway network optimization that takes into account the interrelationships between network structure, train scheduling, and station layout [1]. Integrated optimization strategies that leverage synergistic effects and address challenges arising from evolving passenger demand and travel patterns should be explored. Moreover, the integration of emerging technologies and data-driven approaches can further enhance subway network optimization. Real-time data, predictive analytics, and intelligent transportation systems can optimize train operations, enhance passenger information systems, and provide personalized travel experiences. Future research should focus on the implementation and evaluation of these technologies within the subway system.

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