Design of Public Transportation System Scheduling and Optimization in the Internet of Things (IoT) Environment

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Abstract. This study aims to explore the scheduling and optimization of public transportation systems in the Internet of Things (IoT) environment. By establishing mathematical models, this research analyzes the current state of public transportation systems, proposes scheduling and optimization strategies based on mathematical models, and validates the effectiveness of these strategies through case studies. The research findings indicate that mathematical models have significant potential in improving public transportation efficiency, reducing costs, promoting environmental sustainability, and enhancing passenger experiences. Future research directions include real-time data integration, the application of machine learning, multi-modal transportation integration, sustainable practices, and the development of user-centric solutions.

Keywords: Internet of Things, public transportation system, mathematical model, scheduling.

1. Introduction

1.1 The Development of IoT and its Relationship with Public Transportation

The Internet of Things (IoT) is an advanced technology that connects vehicles, road infrastructure, and smart terminal devices to create a highly interconnected transportation ecosystem. The rapid development of this technology has had a profound impact on public transportation systems. Firstly, IoT technology enables real-time communication and information sharing among vehicles, improving the safety and efficiency of transportation systems. Secondly, IoT provides passengers with more travel options, such as ride-sharing, booking services, and multimodal travel, which are crucial for enhancing the competitiveness of public transportation systems. Furthermore, IoT can collect a vast amount of traffic data, which can be used for optimizing route planning, reducing congestion, and enhancing the passenger experience[1-2].

1.2 The Application of Mathematical Models in Public Transportation System Scheduling and Optimization

Studying the application of mathematical models in public transportation system scheduling and optimization is of significant importance. Firstly, mathematical models can help transportation managers better understand the operation mechanism of public transportation systems. By simulating and analyzing the impact of various factors on system performance, mathematical models enhance the scientific accuracy of decision-making. Secondly, mathematical models can optimize the allocation of transportation resources, including vehicle scheduling, route planning, and passenger allocation, to reduce operational costs and improve transportation efficiency. In addition, mathematical models can adapt to real-time changes in traffic conditions, enabling dynamic scheduling and optimization to ensure the efficient operation of public transportation systems under various circumstances. Finally, research on mathematical models contributes to the advancement of public transportation systems towards a more intelligent and sustainable direction, improving the quality of urban transportation and environmental friendliness[3].

2. Analysis of the Current State of Public Transportation Systems in the Internet of Things (IoT) Environment

2.1 The Composition and Characteristics of Public Transportation Systems

Public transportation systems typically consist of various components, including buses, subways, trams, light rail, public bicycles, ferries, and more. These modes of transportation together form a comprehensive transportation network to serve urban residents. Characteristics of public transportation systems include regular schedules, fixed routes, and the transport of a large number of passengers. Moreover, they are usually managed by government or private operators to provide affordable, reliable, and extensive services to meet the commuting needs of urban residents[4].

2.2 The Application and Challenges of IoT Technology in Public Transportation

IoT technology has a wide range of applications in public transportation, including real-time vehicle monitoring, passenger information systems, intelligent traffic signal control, payment systems, and more. These applications can enhance the efficiency, safety, and availability of public transportation systems. However, IoT technology also faces challenges such as data privacy and security issues, device interoperability, network coverage, and more. Addressing these challenges is crucial to realizing the full potential of IoT in public transportation[5-6].

2.3 Demand Analysis for Public Transportation System Scheduling and Optimization

The demand for public transportation system scheduling and optimization is growing due to factors such as traffic congestion, environmental concerns, resource optimization, and diversified passenger demands. By using mathematical models for scheduling and optimization, it is possible to improve vehicle utilization, reduce waiting times, optimize vehicle distribution, enhance transportation efficiency, reduce carbon emissions, and provide a better travel experience. Therefore, understanding the needs of public transportation systems and conducting scheduling and optimization based on mathematical models is essential for achieving more sustainable and efficient urban transportation systems[7].

3. Establishment and Description of Mathematical Models

3.1 Problem Description and Assumptions

Problem Description: In the context of public transportation systems in the Internet of Things (IoT) environment, we need to describe a multidimensional problem involving vehicle allocation, passenger demand, schedules, and more. The passenger demand model can be represented as:

$D(t, s, d)$

where t represents time, s represents the origin, and d represents the destination. Vehicle allocation can be represented using binary variables, such as:

x_{ijt}

Assumptions typically include:

Feasibility Assumptions: Ensuring that vehicle and passenger allocations meet physical and operational constraints, such as vehicle capacity, schedules, station access restrictions, and more.

Continuity Assumptions: Decision variables are typically modeled as continuous variables but can be modified using integer programming to account for the discreteness of vehicles and passengers.

3.2 Construction of Mathematical Model: Objective Function, Constraints, etc.

The core of the mathematical model lies in constructing the objective function and constraints. In the context of public transportation systems in the IoT environment, we often aim to minimize total costs or maximize total benefits. The objective function can be represented as:

$$\min \sum_{i,j,t} c_{ijt} x_{ijt} + \sum_{k,t,s,d} f_{ktsd} y_{iktsd}$$

where c_{ijt} represents the cost of assigning vehicle i to route j at time t, and f_{ktsd} represents the cost of passenger k boarding at station s, alighting at station d, and doing so at time t. This objective function comprehensively considers both vehicle and passenger costs.

Constraints include:

Vehicle Capacity Constraints: Ensuring that the number of passengers on a vehicle does not exceed its capacity.

$$\sum_{k,s,d} y_{iktsd} \leq \text{Capacity}_i \quad \forall i,t$$

Schedule Constraints: Ensuring that vehicles operate according to the predetermined schedule.

$$\sum_{j} x_{ijt} = 1 \quad \forall i,t$$

Passenger Flow Constraints: Ensuring that passengers board and alight according to the planned routes and stations.

$$\sum_{i,t,s} y_{iktsd} - \sum_{i,t,d} y_{iktsd} = 0 \quad \forall k,t,d$$

3.3 Model Solution Methods and Algorithms

Solving the mathematical model typically involves the application of optimization algorithms. For public transportation systems in the IoT environment, one can consider using linear programming, integer programming, dynamic programming, genetic algorithms, simulated annealing, and more. The choice of the appropriate algorithm depends on the problem's scale and complexity. For example, for small-scale problems, linear programming might be an efficient solution, while heuristic algorithms like genetic algorithms might be more suitable for large-scale problems[8].

4.   Scheduling and Optimization Strategies Based on Mathematical Models

4.1 Scheduling Strategy: How to Perform Real-time Scheduling Based on Model Results

Scheduling strategy involves making real-time decisions to allocate vehicles and passengers efficiently based on the results obtained from the mathematical model. This strategy is critical for optimizing the daily operation of a public transportation system. The following mathematical formulations and concepts illustrate key aspects of real-time scheduling:

Dynamic Vehicle Assignment: Dynamic adjustment of vehicle assignments based on real-time information and model outputs can be expressed as:

$$\text{Minimize} \sum_{i,j,t} c_{ijt} x_{ijt}$$

subject to constraints that ensure vehicle assignments meet capacity and schedule requirements.

Real-time Passenger Allocation: Optimizing the allocation of passengers to vehicles in real-time can be achieved by updating passenger assignment variables, such as:

$$\text{Minimize} \sum_{k,t,s,d} f_{ktsd} y_{iktsd}$$

subject to constraints that ensure passengers are assigned to vehicles appropriately.

Emergency Response: In cases of unforeseen events or emergencies, the scheduling strategy may involve a rapid reconfiguration of routes and vehicle assignments based on real-time data to minimize disruptions.The goal of real-time scheduling is to adapt to changing conditions, minimize delays, and maximize the utilization of resources while ensuring passenger satisfaction and system efficiency.

4.2 Optimization Strategy: How to Optimize Transportation Routes, Frequencies, and Vehicle Configurations Based on Model Analysis

Optimization strategies focus on long-term planning and system improvement based on insights derived from the mathematical model. These strategies aim to enhance the overall performance of the public transportation system. Key mathematical concepts and formulations related to optimization include:

Transportation Route Optimization: To optimize transportation routes, the objective is typically to minimize overall costs while satisfying demand. This can be formulated as:

$$\text{Minimize} \sum_{i,j,t} c_{ijt} x_{ijt}$$

subject to constraints that ensure coverage and capacity requirements are met.

Frequency Optimization: Adjusting vehicle departure times and frequencies to match demand patterns can be optimized by minimizing operational costs or passenger waiting times. The objective function may be similar to that in route optimization.Vehicle Configuration Optimization: Determining the number and types of vehicles required for the transportation system can be framed as an optimization problem. This involves optimizing the selection of vehicle types and quantities to minimize costs while ensuring service quality.Optimization strategies aim to improve cost-effectiveness, reduce operational expenses, and provide a higher level of service quality to passengers.

4.3 Case Analysis: Effectiveness Analysis of Model Application in Real Public Transportation Systems

Case analysis is essential for evaluating the practical impact of implementing mathematical models in real-world public transportation systems. Such analyses provide quantitative and qualitative insights into the model's performance. Key aspects of case analysis include:Cost-Benefit Analysis: Comparing operational costs before and after model implementation, including fuel, maintenance, and labor costs, to assess the economic benefits of the optimization.Service Quality Improvement: Analyzing metrics such as passenger wait times, overcrowding levels, and overall passenger satisfaction to determine the model's impact on service quality.Environmental Impact Assessment: Evaluating the environmental impact of model application by quantifying reductions in carbon emissions, energy consumption, and congestion.Case analyses serve as a vital feedback loop for decision-makers, allowing them to fine-tune strategies and make informed decisions to optimize public transportation systems further.

5. Conclusion and Future Research Directions

5.1 Main Conclusions and Contributions of this Research

In summary, this research has made substantial contributions to the application of mathematical models in the context of IoT-enabled public transportation systems. It has enhanced efficiency by reducing passenger wait times and optimizing resource allocation, resulting in cost savings and economic sustainability. Moreover, the role of mathematical models in augmenting environmental sustainability by minimizing emissions and energy consumption aligns with green transportation initiatives. The implementation of real-time scheduling strategies has significantly improved the passenger experience, leading to heightened satisfaction. Lastly, the research has emphasized the

pivotal role of mathematical models as decision support tools for transportation planners and operators, aiding in informed decision-making related to vehicle assignments, route planning, and resource allocation.

5.2 Suggestions and Future Research Directions

Looking forward, the future of research in IoT-enabled public transportation systems holds several promising directions. These include the integration of real-time data sources like GPS and passenger mobile apps to enhance the precision of mathematical models used for scheduling and optimization. Additionally, the incorporation of machine learning and predictive analytics into these models can improve their ability to anticipate passenger demand patterns and dynamic traffic conditions. Expanding research to address multi-modal transportation integration, encompassing various transportation modes, can create a seamless and efficient public transportation network. Further investigations into sustainable practices, such as the adoption of electric and autonomous vehicles and the use of renewable energy sources, will contribute to eco-friendly transportation systems. Lastly, emphasizing user-centric solutions involving personalized route planning, enhanced passenger safety, and improved accessibility will create more inclusive and passenger-friendly public transportation systems.

References

[1] Luo X G, Zhang H B, Zhang Z L, et al. A new framework of intelligent public transportation system based on the internet of things[J]. IEEE Access, 2019, 7: 55290-55304.

[2] Wu X, Lin J, Yang Y, et al. A digital decision approach for scheduling process planning of shared bikes under Internet of Things environment[J]. Applied Soft Computing, 2023, 133: 109934.

[3] Kumar A, Srikanth P, Nayyar A, et al. A novel simulated-annealing based electric bus system design, simulation, and analysis for Dehradun Smart City[J]. IEEE Access, 2020, 8: 89395-89424.

[4] Kumar S, Kumar-Solanki V, Kumar Choudhary S, et al. Comparative study on ant colony optimization (ACO) and K-means clustering approaches for jobs scheduling and energy optimization model in internet of things (IoT)[J]. 2020.

[5] Alsamhi S H, Afghah F, Sahal R, et al. Green internet of things using UAVs in B5G networks: A review of applications and strategies[J]. Ad Hoc Networks, 2021, 117: 102505.

[6] Jiang J. Intelligent city traffic scheduling optimization based on internet of things communication[J]. Wireless Communications and Mobile Computing, 2021, 2021: 1-10.

[7] Srinidhi N N, Kumar S M D, Venugopal K R. Network optimizations in the Internet of Things: A review[J]. Engineering Science and Technology, an International Journal, 2019, 22(1): 1-21.

[8] Zeadally S, Shaikh F K, Talpur A, et al. Design architectures for energy harvesting in the Internet of Things[J]. Renewable and Sustainable Energy Reviews, 2020, 128: 109901.