

Smart Urban Transit Systems: From Integrated Framework to Interdisciplinary Perspective

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Abstract Urban transit system is an important part of city transportation, which is an interdisciplinary industry, including traffic engineering, operation research, and computer science. To provide smart services for passengers while applying the new technologies, it is necessary to build an optimal transit network and transit service. A smart transit system is processed from strategic planning, tactical planning, operational planning, transit evaluation to marketing and policy. For each stage, large quantities of related literature have been introduced from different perspectives. The aim of this research is to document the main smart urban transit models, topics and implementations for future references and research in each stage. For the planning part, this paper first summarized the objectives, constraints, algorithms, and implications of the models currently in use and classified the objectives and constraints with classic category and new category. The prominent topics and potential research were captured

clearly when comparing the two categories. The methodologies for solving those models were proposed and the genetic algorithm and simulated annealing have been mostly used, which will be helpful for filling the gaps for further research. Despite of the model updates, this study also summarized the application trends such as integrated network design in strategic planning, synchronization and timetable recovery from disruption in tactical and operational planning. To improve the transit system and service, evaluation models on service reliability, service accessibility, timetable robustness, and energy consuming are proposed, which highlight the gap between the idealized service and the real service. Some flexible fare scheme, investments, and commercial strategies are discussed in the financial part. The conclusion highlighted the future scope of the smart urban transit in passenger demand management, travel information service, facility and service optimization and shared mobility, in order to make it more convenient for the passengers and more friendly to the environment.

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1 Introduction

Transportation influences the form of cities and their livability, their economic, social, and environmental characteristics. The increasing transportation demand creates more and more mobility-related problems. Most of the big cities are facing the problem of traffic congestion [1–4]. As urban transit has great possibilities for reducing traffic congestion, offering alternative transportation modes, and contributing greatly to the quality of urban life, urban

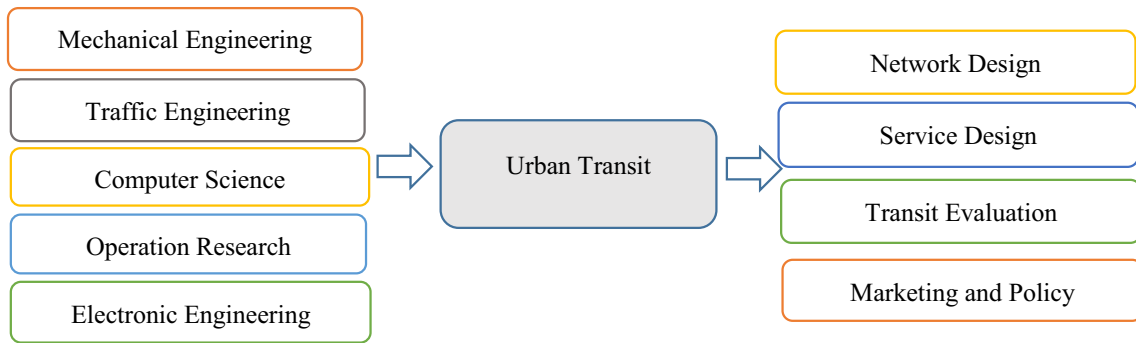


Fig. 1 Integrated framework of related subjects and topic in urban transit

transit system (bus system, rail transit system, and mass transit system) has begun to grow [5, 6]. The set of urban rail systems can be roughly subdivided into the tram, light rail, rapid transit (underground, subway, metro), monorail, commuter rail, and other types such as rail-guided buses in Nancy, France [7].

Transit system is a complex industry including several majors and perspectives, as shown in Fig. 1. Here is a question, how to build the smart transit system considering all the related perspectives? The global problem is not tractable. Not only the technologies but also the transit network and service planning are needed to make the system more smart and intelligent. A set of subproblems including traffic design problem, transit evaluation, and marketing and policy models are proposed to build the smart transit system.

The transit plan is the foundation for a smart urban transit system. Transit network planning problem (TNP) spans every decision that should be taken before the operation of the system. Due to its complexity and objectives, TNP could be divided into strategic planning (network design), tactical planning (frequency setting, timetabling), and operational planning (vehicle scheduling, driver scheduling, and maintenance) [8–10]. On the basis

of transit planning, a smart urban transit system also required attractive marketing policy to attract more residents and also reasonable evaluating methods evaluating to improve the system. In this way, the urban transit system can be classified into these five parts which are connected and interacted with each other as shown in Fig. 2.

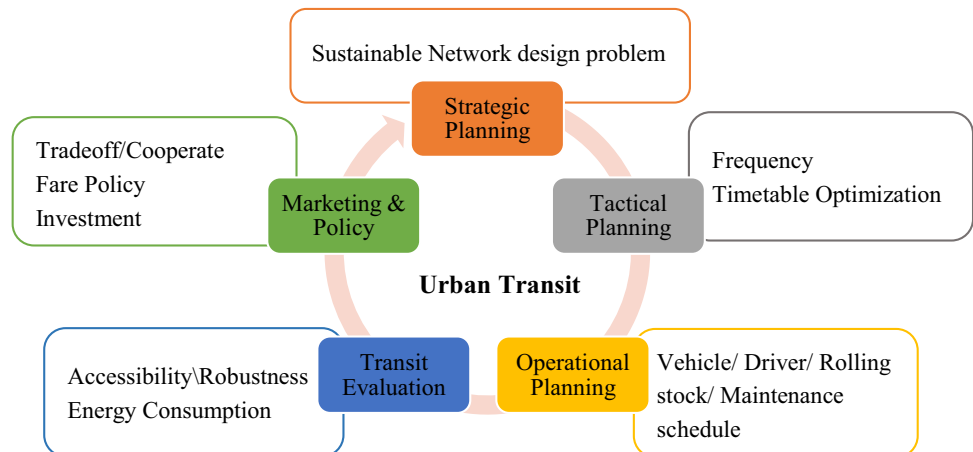
1.1 Strategic Planning (SP)

Strategic planning problems are the initial stage of every smart urban transit system. It defines the network layouts and associated operational characteristics such as rolling stock types and distance between stops. The objective is maximizing the service quality under budgetary restrictions or minimizing the weighted sum of operators’ and users’ costs [9].

1.2 Tactical Planning (TP)

Tactical planning is a way of transferring the transit design to the transportation service, which is a connection between the passengers and operators. Tactical problems focus on the decisions related to services provided to the public, namely the frequencies of service along the routes and the

Fig. 2 Five parts of the transit system



timetables, which could maximize the quality of service [11–13]. These problems are usually solved on a seasonal basis with occasional updates [8].

1.3 Operational Planning (OP)

Operational planning problems focused on providing the proposed service at minimum cost. This topic includes a variety of problems such as vehicle scheduling, driver scheduling, rolling stock schedule, and maintenance schedule.

1.4 Transit Evaluation (TE)

Transit evaluation is a kind of way to obtain the service feedback from the passengers and operators. It also highlights the places where the operators can improve their service. Usually, the transit evaluation contains the transit accessibility, network reliability, timetable robustness, and energy-consuming evaluation.

1.5 Marketing and Policy (MP)

In order to make more profit for the society and residents, some works on marketing strategies such as fare policy, investment strategies and trade-offs, and cooperation with other transportation modes are studied.

The aim of this paper is to review state-of-the-art models and approaches for solving these urban transit problems. This review is not exhaustive as it aims to mostly cover the recent contributions that have been applied or have potential to be applied from our viewpoint. Other than reviewing the topics and technology, we also review the solution methods for a different aspect of the urban transit system. This allows comparisons of solution methods of different problems in various classes of the urban transit system and proposes new algorithmic research directions.

The rest of the paper is organized as follows: Sect. 2 reviews the urban transit network planning problem studied in the literature. Section 3 mainly depicts the timetable optimization problems from different perspectives. Section 4 describes the methods evaluating the transit service. Section 5 presents the research on transit marketing and policy. Section 6 depicts the solution method used in Sects. 3 and 4. Finally, the overall view of the research and further research directions are presented in Sect. 7.

2 Strategic Planning: Sustainable Urban Transit Network Design

Network design was firstly formulated by Dantzig [14] as a fixed charge transshipment problem. This problem has been well studied with a full spectrum of strategic, tactical,

and operational decision-making situations [9, 14–16]. The aim for the network design problem is to find an optimal allocation and utilization of resources to achieve a certain goal [17], such as improving traveler mobility, reducing air/noise pollution, avoiding accidents, and increasing accessibility to meet passengers' movement requirements [9]. Generally, the objective of network design problem is to minimize the total travel time or the generalized travel cost.

In addition to basic objectives, several other perspectives are considered in practice. These perspectives include: (1) ensuring adequate coverage in the network; (2) ensuring minimum frequencies of service; and (3) any other design considerations such as the availability of infrastructure or right-of-way for routes [18, 19].

A summary of urban transit planning studies ordered by time is presented in Table 1 and Fig. 3. From the beginning of Table 1, budget and passenger demand are main constraints for network design model. Transit planning aims to find a balance between passengers benefit and operation cost [20–22]. Recently, based on the abundant data provided by data collection systems, it has become possible to analyze the passenger demand in various dimensions such as time-dependent demand and service reliability, which provide new aspects to design a better network. Some attempts are proposed to solve the flexible demand models [21, 23–25]. For the passengers, they hope the transit network could cover a larger service area and have high accessibility [26–28] and fewer transfers [22]. In addition to travel demand and accessibility, the stochastic travel time [29, 30], robustness of network [31], and multi-route transit lines [32] are taken into consideration in network design models.

2.1 Discussion

2.1.1 “Passenger-Environmental Friendly” Design

There is a big change in network designing concept. In the past few decades, facilities and infrastructures, civil construction, and budgets have become the priorities. In the last 10 years, the passenger demand and travel experience have raised more attention. Network designers are trying to build a passenger-friendly and environmental-friendly network. In the passenger-friendly network design model, the objective is not only the travel demand, but also the travel cost, which means fewer transfers in the path and more direct shortest path for the passengers are designed to enhance the accessibility of the network. To reduce the emission of the transportation, the environmental costs are addressed in those models. Some research examined how the operational characteristics of urban transit systems affect both costs and greenhouse gas emissions, which

Table 1 A summary of urban transit network design studies

References	Constraints	Objective(s)	Demand (fixed/uncertain)	Solution algorithm	Network size
Kuah and Perl [38]	Route capacity Fleet size Route length Route frequency	Min. total travel cost	Uncertain	Heuristic	A network with 55 bus stops
Chien et al. [39]	Capacity Budget Headway Demand satisfaction	Min. total cost	Fixed	Genetic algorithm	A realistic urban networks with 4 km long and 10 km wide
Ceder [40]	Route length Shortest path deviation	Min. operator and users costs Min. fleet size	Fixed	Heuristic	–
Wan and Lo [32]	Service frequency Bus capacity	Min. operation costs	Fixed	Cplex Heuristic	A network with 10 nodes and 19 undirected arcs
Lee and Vuchic [41]	Timetable Frequency Demand satisfaction	Min. user travel time	Fixed	Iterative approach	Network in Rea's paper
Fan and Machemehl [21]	Headway feasibility Load factor constraint Fleet size Trip length Numbers of routes	Min. the sum of user and operator cost Min. unsatisfied demand costs	Uncertain	Genetic algorithm	A network with 93 nodes
Ukkusuri et al. [31]	Budget Demand satisfaction	Min. total system travel time Min. passenger travel time (UE)	Uncertain	Heuristics Genetic algorithm	Harker–Friesz (HF) network Nguyen–Dupuis network
Zhao and Zeng [34]	Headway feasibility Fleet size Route length Load factor	Min. weighted sum of users' and operator costs	Fixed	Heuristic, simulated annealing	A network in Switzerland
Guihaire and Hao [22]	Feasibility Constraints Timetable structure Complete assignments Group interlining	Min. number of vehicles Min. waiting and transfer Min. headway evenness defaults	Uncertain	Iterated local search	A network with 55 bus stops and 4 railway stations
Fan and Machemehl [42]	Headway feasibility Load factor Fleet size Trip length	Min. total user cost Min. total operator cost	Fixed	Tabu search	A network with seven travel demand zones and 15 road intersections
Lium et al. [43]	Fleet capacity Conservation of flow Cyclic schedules	Min. operation cost	Fixed and Uncertain	Monte-Carlo simulation	A small case with 12 OD pairs
Fan and Mumford [44]	Number of lines	Min. travel time Min. transfers	Fixed	Hill climbing Simulated annealing	Mandl's Swiss road network

Table 1 continued

References	Constraints	Objective(s)	Demand (fixed/uncertain)	Solution algorithm	Network size
Fan and Machemehl [45]	Trip length Max number of routes Headway Load factor Trip length Spatial equity	Min. user cost, operator cost, and unserved transit demand	Fixed	Genetic algorithm	A network with 28 travel demand zones and 65 nodes
Gallo, et al. [46]	Timetable Budget Capacity Assignment	Min. the weighted sum of user and operator costs	Uncertain	Heuristic local search and scatter search algorithm	A small network Campania Regional Authority rail network
Cipriani et al. [24]	Bus capacity Frequency Route length	Min. user and operator costs Min. the external costs	Uncertain	Heuristic, genetic algorithm	Network in Urban area of Rome
Cipriani et al. [47]	Bus capacity Frequency Route length	Min. the sum of operator and user costs	Fixed	Heuristic, genetic algorithm	Network in Urban area of Rome
Miandoabchi et al. [48]	Budget Connection	Max. total user benefit Max. bus demand share Max. bus demand coverage Min. averaged cost of bus trips	Fixed	Pareto optimal solutions and simulation annealing	A network with 8 nodes and 11 links
Yu et al. [27]	Route length Demand satisfaction Route type	Max. total demand density of the route considered direct trips and transfers	Fixed	Ant colony optimization	Dalian City
Yan et al. [29]	Demand covering Feasibility constraints Load factor Fleet size Travel time reliability	Min. operator costs	Fixed	Simulated annealing	Swiss network
Yao et al. [30]	Cycle time Flow conservation Demand satisfaction	Max. the efficiency of passenger trips	Fixed	Tabu search	A network with 30 nodes and 49 links
Hassannayebi et al. [25]	Timetable Structure Conservation of flow	Min. expected passenger waiting times	Uncertain	Simulation Genetic algorithm	Tehran metro network
Tong et al. [26]	Travel time budget Space–time flow Activity performing Coupling constraints	Max. the number of accessible activity locations in space–time network	Fixed	Lagrangian decomposition	Chicago sketch network with 933 nodes, 2950 links
Zarrinmehr et al. [49]	Shortest path assignment	Max. transit share of the demand Min. operator cost	Uncertain	Greedy solution Pareto optimal	Chicago sketch network

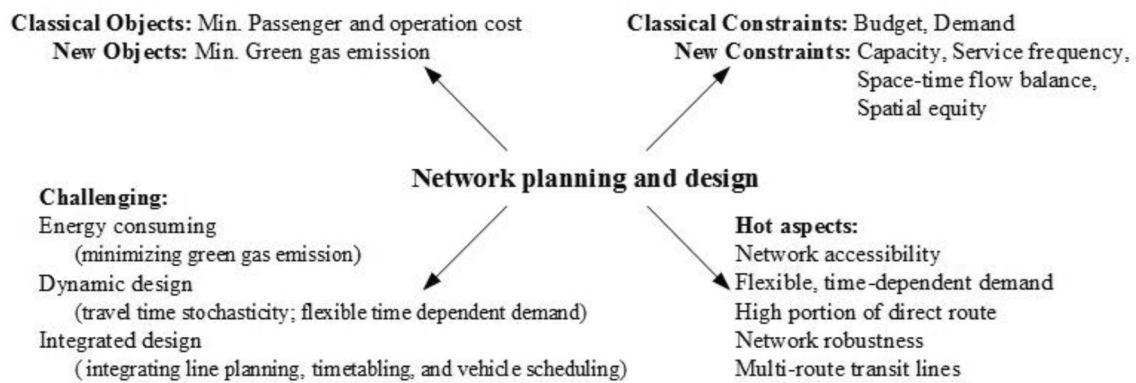


Fig. 3 Objects, constraints, hot topic, and challenges in network planning and design process

could be used to optimize the network design of existing bus service or help to select a mode for minimizing both costs [33].

2.1.2 Dynamic and Detailed Design

To represent a more realistic network, vehicle stochasticity and travel stochasticity are considered in recent network design work. Considering the stochastic characters of travel time can help securing transfer possibilities and minimizing passengers' transfer time. In spite of travel time stochasticity, some more detailed criteria are taken into consideration such as the network robustness and the time-dependent passenger demand. All these detailed information in the network design could represent passenger profits in the network, and the design will provide better service for the passengers [18].

2.1.3 Integrated Network Design

The network design relates to the timetable scheduling and train/bus operation. In order to make the design satisfy and facilitate the operation tasks, integrated design ideas became very popular. The integrated design also can be taken as a network optimization that combines transit network, vehicle headways, and timetables [34–37]. This problem is more difficult and complex than the normal network design problem. A heuristic method combined with simulated annealing, tabu, and greedy search methods could be used to solve this problem.

3 Tactical and Operational Planning: Transit Operation and Services

3.1 Timetable Design and Optimization

Timetable generation is the following process of transit network strategic planning, in which the departure time of

each trip is determined. For most of timetable optimization problems, the objectives are to minimize the passenger waiting time or transfer time [50–53], despite meeting with the flexible travel demand [54–61]. Meanwhile, a major complication in transit network timetabling occurs when schedules are intended to be coordinated at a transfer stop or terminals, named timetable synchronization [16, 62, 63]. The objectives of these models are to maximize the number of synchronizations in the transfer stations or maximize the direct transfer passengers and to minimize the passengers' transfer time and waiting time in the transfer station. A special case in timetable synchronization is the first and last train organization [6, 64, 65]. When generating the timetable, it is also important for the operators to minimize the operation cost and build up the environmentally friendly timetable [66–71]. For the models mentioned in those papers, most of them share same constraints, including: (1) dwell time in the station; (2) the time window of the train, which gives out the upper and lower departure time of the train in any station; and (3) train consecutive trip, which gives out the order of the first train and consecutive train. For tram systems, which has the correlation with road traffic their timetabling models have to consider the intersection signal timing and the trade-offs between the tram travel time and the roadway traffic delay [72, 73]. Table 2 and Fig. 4 summarize the related literature on obtaining passenger travel time, schedule synchronization, first and last train optimization, and energy consumption, respectively. Summarizing from the related literature, there are two research directions that have become popular in recent years: cyclic timetables and timetable recovery from disruption.

1. *Cyclic Timetable* A cyclic timetable repeated every standard period [74, 75]. The cyclic timetable is widely used in Europe railway system. Serafini and Ukovich [76] firstly introduced the Periodic Event Scheduling Problem (PESP), by which periodic timetabling instances may be formulated in a very compact way

Table 2 A summary of urban transit network schedule optimization

References	Constraints	Objective(s)	Solution method	Network size
(a) Min travel time				
Chang et al. [53]	Total trip distance Schedule Passenger demand Capacity Fleet size	Min. operating cost Min. passenger travel time loss	Fuzzy mathematical programming	Taiwan high-speed railway system
Liebchen [51]	Running dwell time Passenger demand Infrastructure information Min. turnaround times	Min. operation cost Min. transfer and waiting	Mathematical optimization model	Berlin subway network
Wong et al. [50]	Headway Travel time Run dwell time Collision avoidance	Min. total transfer waiting times	Optimization-based heuristic solution approach	MRT in Hong Kong Focus on 4 lines
Shafahi and Khani [52]	Min. possible waiting time Headway	Min. waiting time at transfer stations	Genetic algorithm	Mashhad City bus network
Niu and Zhou [55]	Timetable Cumulative passenger Non-decreasing flow Time window Remained passenger Capacity Variable demand	Min. the total number of waiting passengers and weighted remaining passengers.	Genetic algorithm	No. 8 subway line in Guangzhou City
Barrena et al. [56]	Flow conservation Capacity Train order Train number limitation Time window	Min. the total waiting time of passengers	Branch-and-cut algorithm	Line C5 of Madrid Metropolitan Railway
Barrena et al. [57]	Dwell time Train order Variable demand Headway Time window	Min. total passenger average waiting time	Adaptive large neighborhood search metaheuristic	Line C5 of Madrid Metropolitan Railway

Table 2 continued

References	Constraints	Objective(s)	Solution method	Network size
Sun et al. [54]	Last service Discrete departure time Operation safety Variable demand Capacity Last service Headway Service level	Min. total waiting time	Cplex	EW line in Singapore
Shang et al. [60]	Individual-based passenger demand Train capacity Platform capacity Timetable	Min. the maximum passenger waiting time	Lagrangian relaxation decomposition approach	Beijing metro line Batong
Shi et al. [61]	Dynamic passenger demand Train capacity Platform capacity Timetable Passenger flow control	Minimize the total passenger waiting time at all of involved stations	local search and Cplex solver	Beijing metro line Batong
(b) Schedule synchronization				
Ceder et al. [16]	Train time window Headway	Max. the number of simultaneous bus arrivals at transfer stations	Heuristic algorithm	Israel bus network with 7 bus routes and 14 bus routes
Eranki [62]	Train time window Headway	Max. number of simultaneous arrivals	Heuristic algorithm	A network with 6 routes
Cevallos and Zhao [106]	Train time window	Min. total transfer times	Genetic algorithm	Broward County Transit
Ibarra-Rojas and Rios-Solis [107]	First and last trip Headway Consecutive trip	Max. the arrivals of direct bus lines	Iterated local search Hill climbing	Bus network of Monterrey, Mexico
Wu et al. [108]	Train time window Headway Waiting and travel time	Min. the maximal passenger waiting time	Genetic algorithm	Beijing metro network
Wu et al. [109]	Train time window Headway Transfer demand Transfer feasibility	Max. number of direct transfer passengers Min. maximal timetable deviation	Non-dominated sorting genetic algorithm	Shenyang, China. A real bus network with 10 lines and 3 transfer nodes

Table 2 continued

References	Constraints	Objective(s)	Solution method	Network size
Guo et al. [110]	Train operation Headway Transfer efficiency Passenger transfer status	Max. the number of synchronizations	Particle swarm optimization Annealing algorithm	Beijing metro network
Li et al. [75]	Dynamic passenger load	Min. passenger cost for the joint dynamic model	Model predictive control	Beijing metro line 9
(c) Last train and First train schedule				
Kang et al. [6]	Transfer time Train operation Operation time	Max. connections and less transfer waiting time	Genetic algorithm	A part of Beijing metro network
Dou et al. [64]	Train time window Last train schedule	Max. number of smooth transfers	Cplex	8 bus lines in Singapore
Kang and Zhu. [111]	Dwell and run time Train time window Operation closed time	Min. the standard deviation of transfer redundant times	Heuristic algorithm Branch-and-bound	Beijing metro network
Kang et al. [112]	First connection time Train time window Transfer waiting time	Min. number of missed trains for the first train	Local search heuristic	Beijing metro network
Guo et al. [65]	Train time window Transfer time	Min. total waiting time	Sub-network connection method	Beijing metro network
(d) Energy consumption				
Albrecht and Oettich [66]	Speed limit Dwell time Journey time	Min. waiting time and energy consumption	MATLAB Simulink	A part of the suburban railway of Dresden, about 17 km
Peña-Alcaraz et al. [67]	Train movement	Max. use of regenerative-braking energy	–	Line 3 of the Madrid underground system
Cucala et al. [69]	Timetable Speed Punctuality	Min. energy consumption Min. uncertainty in delays	Genetic algorithm	Spanish high-speed line
Su et al. [113]	Dwell time Trip time	Min. energy consumption	Numerical analysis	Beijing Yizhuang metro line
Li and Lo [68]	Speed file Timetable	Min. net energy consumption	Genetic algorithm	Beijing Yizhuang metro line
Yang et al. [114]	Speed file Schedule Cycle time	Min. the trains' energy consumption with dwell time control	Genetic algorithm, allocation algorithm	Beijing Yizhuang metro line

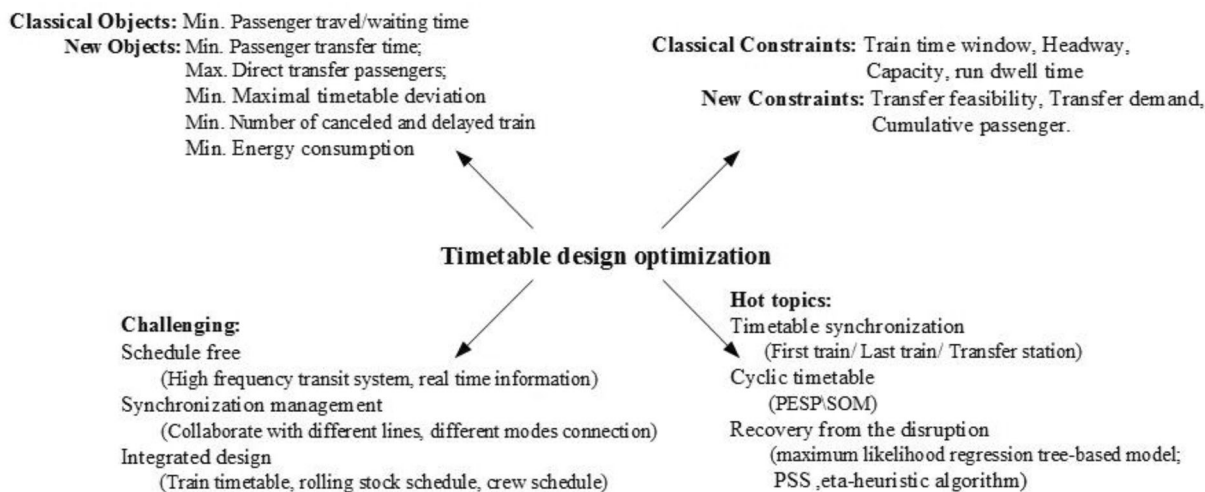


Fig. 4 Objects, constraints hot topic, and challenges in timetable design and optimization

and was applied widely later [51, 77, 78, 82]. Sels et al. [79] derived a PESP model to minimize the total passengers' travel time in cyclic timetables, and macroscopic simulations were utilized to generate a robust railway timetable. The new periodic timetable is able to save 3.8% of passenger average journey time in Belgian railway. Liebchen and Möhring [80] extended PESP by two features, a linear objective function and a symmetry requirement. Kroon et al. [81] considered the stochastic disturbances in operation and described a Stochastic Optimization Model (SOM) that can be used to allocate the time supplements and the buffer times in a given timetable in such a way that the timetable became maximally robust against stochastic disturbances, and Maróti [83] used a branch-and-bound approach to shorten the computation time of SOM.

2. *Timetable Recovery from Disruption* Considering the bus or train delay, the real-time rescheduling problems and disruption management for rolling stocks and crew schedule become important [84–89]. Cacchiani et al. [90] presented an overview of recovery models and algorithms for real-time railway disturbance and disruption management. Weng et al. [91] developed a maximum likelihood regression tree-based model to predict subway incident delays, which is beneficial for subway engineers looking to propose effective strategies for reducing subway incident delays, especially in cities with huge public travel demand. Albrecht et al. [92] described how the Problem Space Search (PSS) metaheuristic can be used for large-scale problems to create quality timetables in which both train movements and scheduled track maintenance are simultaneously considered. Veelenturf et al. [93] formulated an integer linear programming model for solving the timetable rescheduling problem, which minimizes the

number of canceled and delayed train services while adhering to infrastructure and rolling stock capacity constraints. Kroon et al. [94] considered the passenger flow change in the large-scale disruption. They described an iterative heuristic for solving the rolling stock rescheduling model with dynamic passenger flows. Yin et al. [95] proposed the static disruption management problems and three levels of attack strategies. Jin [96] presented an optimization-based approach that responds to degradations of urban transit rail networks by introducing smartly designed bus bridging services.

3.2 Discussion

3.2.1 Integrated Timetable Design

Timetable generation is correlated with other scheduling phases (timetable, rolling stock, and crew rescheduling). Most of the research considers one scheduling phase. Only few of them integrated two phases, such as timetable and rolling stock scheduling or vehicle and duty scheduling [37, 97–102]. For the future research, a nonlinear multi-objective model for optimal schedule could be designed, which is able to maximize schedule reliability and minimize energy consumption, rolling stock, and crew deployment. Another possible strategy for obtaining a full integration is to design a framework that consists of a closed loop in which each rescheduling phase is solved by an efficient algorithm to find a feasible solution and get feedback from the other phases in order to obtain a better feasible solution for the whole system [90].

3.2.2 Synchronization Management

The target of optimizing operation is to reduce transfer time and provide convenience for the passengers. For recent studies, transfers are usually synchronized in one point of the network [103, 104]. In the network, synchronization management is not only required for different lines, which minimize the transfer for the passenger, but also between different modes, the connection between the metro and feeder bus. In this way, the network-mode-wide optimization of the transfer and synchronization would be desirable.

3.2.3 Schedule-Free Operation

High-frequency transit systems are essential for the socioeconomic and environmental well-being of large and dense cities. Based on the high frequency of the transit, Sánchez-Martínez et al. [105] developed a schedule-free paradigm for high-frequency transit operations, in which trip sequences and departure times are optimized to maximize service quality while satisfying operator resource constraints.

4 Transit Service Evaluation from Both Design and Operation Perspectives

Service evaluation is the way to find out the weak point of the schedule and operation strategy [115] and improvements for the social efficiency [116]. Service evaluation contains comfort, convenience, travel conditions, environment, etc. [117, 118]. Litman [119] studied how transit service quality factors affect travel time values and transit ridership. The evaluation analysis is mostly based on the survey data or operation data. Awasthi et al. [120] presented a three-step hybrid approach based on SERVQUAL and fuzzy TOPSIS for evaluation which could provide solution under partial or lack of quantitative information from the survey. Based on the passenger data to evaluate the drawbacks of scheduled timetables, Jiang et al. proposed a simulation-based model to estimate the passenger delays in transit network [121, 122]. Reviewing the recent research about transit evaluation, they can be categorized as service reliability and accessibility, timetable robustness, and energy evaluation.

4.1 Accessibility Evaluation of Transit Network and Services

Accessibility is essential to ensure equal opportunities for all people in society [123–126]. Improving the accessibility of transit system has the potential to increase the

attractiveness of public transit to current and prospective riders. Xu et al. [127] defined the Expected Locational Accessibility (ELA) of urban transit networks for commuters, measured by the sample-test-statistics method and the topological analysis method. De Oña et al. [128] proposed a Structural Equation Model (SEM) approach for evaluating the quality of service perceived by users of a bus transit service with 1200 collected surveys. The results showed the service has the highest weight, while comfort and personnel parameters have little weight in the model. And conventional evaluation practices generally assign the same time value regardless of travel conditions, and the impacts of comfort and convenience are underestimated.

4.2 Reliability Evaluation of Timetable

An understanding of service reliability, which includes routes, stops, punctuality, deviation, and evenness [129], is necessary to develop strategies that help transit agencies provide better services [129–131]. Diab et al. [132] made up the gap between passengers' and transit agencies' perspectives on service reliability. Chang et al. [133] analyzed the bus traffic signal priority strategies with their own *INTEGRATION* simulation package. Simulation results indicated that the improvements of 3.2% in bus service reliability will increase 0.9% for bus efficiency. Van Oort [134] considered the additional travel time as the indicators for the service reliability and demonstrated that traditional indicators lead to wrong indications. The approach proposed in Eklund and Cook [135], which has the capability of handling the uncertainty of transit operations based on a multi-objective evolutionary algorithm using a dynamic Bayesian network, applies preventive strategies to forestall bus unreliability.

4.3 Robustness Evaluation of Timetable

Urban transit systems experience high capacity consumption during large parts of the day resulting in delay-sensitive traffic systems. One fundamental challenge is, therefore, to assess the robustness and find strategies to decrease the sensitivity to disruptions [136–138]. Andersson et al. [139] proposed a new robustness measure based on Robustness Critical Points (RCP) in the timetable and applied the new model to the Swedish railway line. Goerigk et al. [140] analyzed the impact of different line planning models by comparing their impact on timetables and their robustness against delays. For the Dutch railway network, Corman et al. [141] evaluated the “shuttle” timetable reliability with a thorough assessment and Goverde [142] described a stability theory to analyze timetables on sensitivity and robustness to delays based on a linear system description of a railway timetable in max-

plus algebra. Dewilde et al. [143] introduced the minimizing the real travel time as a practical robustness measure. The results indicate an average improvement in robustness of 6.2% together with a decrease in delay propagation of about 25%.

5 Marketing and Policy from an Industry Perspective

Passengers are quite sensitive to the price strategy [144–148]. Analyzing the passenger behavior before and after new price scheme, the acceptability of urban transport pricing strategies could help to make more reasonable price policy [149–151]. Delbosc and Currie [152] focused on the fare evasion. They used a quantitative cluster analysis to segment fare evasion behaviors into three categories, which show distinct personality and behavioral characteristics. A model built by Bianchi et al. [153] tested the impact of different price levels on patronage by period based on the new price strategy of Santiago Metro. Li et al. [154] proposed a network-based model for investigating the optimal transit fare structure under monopoly and oligopoly market regimes with uncertainty in the network. Wang et al. [155] assessed the influence of ridership and revenue of Beijing metro new distance-based fare policy. Instead of flat fare, researchers try to make a flexible pricing strategy which will attract more passengers and make higher revenue [156, 157]. Some special ticket schemes are put forward for the university student [158, 159], for example, students and faculty from University of Minnesota; twin cities could enjoy three stations free ride in the campus. Brown et al. [160] evaluated the results of the Un-limited Access Program at the University of California, Los Angeles (UCLA), which provides fare-free transit service for all students.

In order to get more investments for the urban transit system, some marketing strategies are studied [161–163]. Schmekel [164] analyzed the strategic importance of retail investment in Asia and its implications for the Metro Group in Asia. Chakrabarti and Giuliano [165] took Los Angeles Metro bus system to analyze the transit patronage from service reliability.

Transit is not the only mode that provides transportation supply. Parking and Ride (P + R) is a good way to achieve the cooperation between cars and transit. Hamre and Buehler [166] evaluated the relationship between commuter benefits and mode choice for the commute to work using revealed preference data on 4630 regular commuters, including information about free car parking, public transportation benefits, and bike parking at work in the Washington, DC region. Chen et al. [167] developed the location-based service application to help P + R riders choose the best depart train station. Du et al. [168] modeled

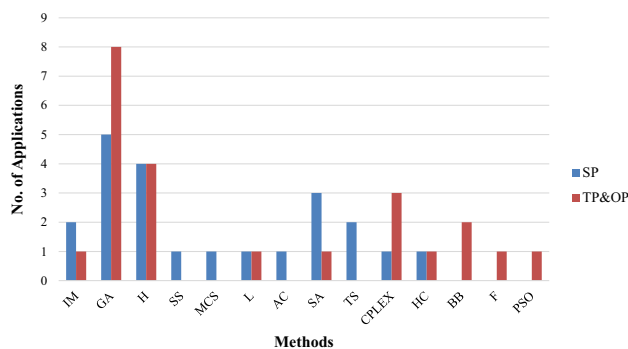


Fig. 5 A summary of methods used in urban transit planning. *IM* iterated local search, *GA* genetic algorithm, *H* heuristic, *SS* scatter search algorithm, *MCS* Monte-Carlo simulation, *L* Lagrangian decomposition/relaxation, *AC* ant colony optimization, *SA* simulated annealing, *TS* tabu search, *HC* hill climbing, *BB* branch-and-bound algorithm, *F* fuzzy mathematical programming, *PSO* particle swarm optimization

park and ride services in a multi-commodity discrete/continuum transport system with elastic demand.

6 Review of Solution Techniques Solving Smart Urban Transit Models

Transit planning models are usually considered as an optimization problem. Solutions about these models are listed in Tables 1 and 2. In this section, we only discussed the solution used in optimization problems in Sects. 2 and 3. Normally, the solution can be classified into three categories: (1) exact or mathematical methods, (2) heuristics, and (3) metaheuristics. Exact methods, such as the branch-and-bound method and Lagrangian decomposition method, highly rely on the model mathematical properties. Although some of them have been applied to realistic and large networks, the computation efficiency is still a big shortage to solve the real-size network problem. Heuristics are usually developed for the large network application because of short computation time, but the one thing need to consider is the convergence. Metaheuristics such as simulated annealing and the use of a genetic algorithm were proposed based on analogies to physical, chemical, or biological process [18]. Metaheuristics process could identify the nearly global optimal solutions more efficiently. Figure 2 summarizes the applications of some metaheuristics and mathematical methods in the literature in Sects. 2 and 3.

Figure 5 shows that the heuristics and metaheuristics are mostly used to solve the planning problems in the urban transit system. Although a large collection of metaheuristic application to these problems can be found in the literature, the applications are very limited to a very few numbers of classical metaheuristic such as GA and SA and none

classical metaheuristics such as TS and AC. Among these methods, the GAs and SAs have been mostly used. Further research on testing those methods hasn't been applied and could be studied in the later research. There are limited studies that have employed a mathematical method for obtaining solutions. For example, the branch-and-bound algorithm and MIP solver in the Cplex are used to solve some mixed integer problem. Although they can provide an exact solution, they can usually be applied to some small network.

7 Discussion and Conclusion

A smart transit system contains sustainable urban transit network design, high-level operation service, reasonable evaluation, flexible marketing and policy. This study focused and summarized the models and research in each part. In the network design process, this research listed the objectives, constraints and algorithms for network design model. Despite satisfying the traffic demand and accessibility, designers consider more on the environment, social profits, and the operation schedule. To provide better service after summarizing and analyzing the operational updating model, the schedule synchronization, cyclic timetable, minimal energy consumption, and timetable recovery from the disruption are considered as new aspects for the tactical and operational planning stage. To improve the transit system and service, this study summarized the evaluation models on service reliability, service accessibility, timetable robustness, and energy consuming are proposed, which highlight the gap between the idealized service and the real service. Meanwhile, the urban transit system is a complex industry and needs financial investments. Some flexible fare scheme, investments, and commercial strategies are applied to the transit system to support the sustainable development. From travel demand, system synchronization to operation control, the transit systems are facing challenges on how to improve the travel efficiency and decrease travel energy consumption. There are several research topics that are necessary for the future study.

7.1 Passenger Demand Management and Travel Information Service

7.1.1 Passenger Behavior Analysis and Rescheduling for Transit Interruption

A lot of research has focused on passenger behavior and transit service for normal daily transit operation. However, transit system is not always stable and train delay or signal failures may happen. To deal with those disruptions, it is

necessary to learn the passenger behavior pattern such as the behavior in the station and route choice in the network. Following the spatial and temporal passenger flow on the network, it is possible to provide temporary and emergency rescheduling model and algorithm for the delayed passengers.

7.1.2 Data-Driven Passenger Demand and Behavior Analysis

With the development of the communication technology and computer science, the passenger travel data and operation data can be collected and updated in a short time interval [169]. For the transit system, the automated vehicle location (AVL) systems, automatic fare collection (AFC), and automatic passenger collection (APC) opened new venues in operations and system monitoring. The various uses of the data could be classified into three levels: strategic, tactical, and operational level. For the strategic level, data can be very useful to transit planners, from the day-to-day operation of the transit system to the strategic long-term network planning [170]. In the tactical level, the data can be the input for the service adjustments and network development. In the operational one, it is possible for the operators to evaluate the operation performance, service level, and service reliability [171–175]. Meanwhile, those huge amount of data provide better opportunity for the researchers to track and estimate passenger behaviors in the network [176, 177], such as the spatial–temporal density [178, 179], path choice [180, 181], trip pattern and trip chain [182–184], and transfers [185]. Operation agencies could provide better and smarter operation strategy for passengers, such as a reinforcement learning-based coordinated passenger inflow control strategy [186].

7.1.3 Heterogeneous–Homogeneous Passenger Forecasting Models

Detailed spatial and temporal passenger distribution patterns are the foundation for the passenger forecasting model. A pile of research has been worked on the spatial and temporal passenger behavior from statistical to dynamic. From those studies, most of them focus on the commuters in transit system during the peak hour, which is the majority proportion of passengers. The research results provide nice homogeneous passenger forecasting models. For the off-peak hour, the passenger classifications are more vivid. It is more diversity in route choice, spatial distribution, and temporal distribution. In this case, it is necessary to provide heterogeneous forecasting models to cover the passenger diversity.

7.1.4 Real-Time Service Information

Real-time information helps the passengers to update their trip plan. Watkins et al. [187] developed the *OneBusAway* system which can estimate the bus arrival time [188] and analyze the passenger perceived and actual wait time impacted by real-time information. Zhang et al. [189] analyzed the impact of Stockholm metro with the real-time crowding information. Though these services are widely used and improved the performance of the public transportation, there are some blanks need to fill. For instance, it is still challenging to calculate the overall transit ridership.

7.2 Transit Facility and Service Optimization

7.2.1 Operation Energy Consumption Control

The transit system is motivated by electricity. In Beijing, compared with other industries, Beijing metro is on the top place on energy consumption. To reduce the energy consumption, it is necessary to optimize the train operation speed based on the traction curve. From the research above, some researchers have been working on the schedule optimization with consideration of environmental costs. Meanwhile, some technologies for train and network design such as regenerative braking technology, energy-saving slope, and automatic train operation and control system have been applied in the transit system.

7.2.2 Data-Driven Rescheduling Models

In addition to passenger analysis, AVL provides bus and train real-time position and makes the real-time control and real-time information (RTI) possible [190, 191]. The passengers could use RTI to change their path in time based on the congestion condition in the network, and for the operators, they could deal with unexpected variations in the schedule and improve the performance of the system. Nesheli et al. [192] invested and analyzed the benefit from real-time operational tactics. In 2015, collaborating with Ceder they proposed transfer synchronization to improve the reliability of public transportation [193].

Over the years, Geographic Information System (GIS) technology has been implemented for a variety of purposes within the transit industry. Recently, the GIS has been widely used in accessibility analysis such as the walking accessibility between alternative neighborhood designs [194] and transport accessibility disadvantage [123]. The data and results in transit have the spatial characteristic. To demonstrate the data more clearly and directly, some visualization tools based on GIS have been developed to explore spatial variations in data [195]. The visualization

results also provide a better way to find out the character of the data and a better understanding of the data.

7.2.3 Integrated Operation Design

Transit network is the combination of passengers, stations, transit lines, trains, and service staff. Timetables, rolling stock plans, maintenance planning, and crew scheduling are dominated operation schedules for the transit system. All of these components have correlations with others. While there are some classical models which performed well in each part individually, it is still necessary and challenging to propose an integrated optimization model to consider all of these components together and provide efficient and environmental-friendly transit service for passengers.

7.3 Shared Mobility and Emergency Control

7.3.1 Emergency Control

While most of the models showed excellent results in improving the schedule and operation performance, most of the applications are off-line or post-evaluation. Transit system needs a quick response to the accident and disruption. It is necessary and will be a large challenge to apply the academic models and algorithms into the real-time operation facing the interruption in the system.

7.3.2 Shared Mobility

Technology is transforming transportation. Bike sharing, car sharing, and rider sourcing services provided by companies such as Uber and Lyft are all shared modes, which have a strong relationship with the public transit [196, 197]. The shared mobility, especially the bike sharing, could efficiently solve the *last one-kilometer* problem. Jin et al. [198] showed out that the metro network resilience to disruptions can be enhanced significantly from localized integration with feeder bus services. In recent 3 years, another kind of “public mode,” bicycle-sharing programs, such as *Mobike* (Beijing), *CityCycle* [199], and *NiceRide* (Minneapolis), has received increasing attention with initiatives to increase bike usage, better meet the demand of a more mobile demand, and lessen the environmental impacts of our transportation activities [200–203]. After studied 7 cities (Austin, Boston, Chicago, Los Angeles, San Francisco, Seattle, and Washington, DC.), shared modes complement public transit, enhancing urban mobility, especially when public transit runs infrequently or is not available and will continue to grow significantly. In the future, the public entities such as buses, tram, and metro should collaborate with the shared

mobility modes to ensure that benefits could be widely and equitably shared. Technology and emerging approaches are urgent for public sector and private operators' collaboration to improve paratransit services [196, 197].

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