

## Review Article

# Review of Urban Transportation Network Design Problems Based on CiteSpace

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This paper provides a comprehensive review of urban transportation network design problems according to CiteSpace, including main problem classifications, mathematical models, and solution methods obtained from CiteSpace clusters. The review attempts to present the systematic picture of urban transportation network design and show the future directions of it.

## 1. Introduction

The urban transportation network system is composed of four categories: facility network, route network, organization network, and demand network. The intertwined networks form the essential base for the human interaction in social and economic activities and even the urban architecture. In the context of urban transportation network, the traffic nodes constitute a facility network, the traffic lines make up a route network, and the combination of nodes and lines forms organization network, including urban road network, urban public transportation network, urban external transportation network, and passenger and cargo transportation hubs. Urban transportation network is an important issue both for human activities and civil logistics. In particular, under the background of sustainable development, the network design plays a significant role in highly efficient activities and can contribute to less environment-related problems.

Urban transportation network design problem (UTNDP) is so complicated and practically important that it has been studied since the last five decades. As a result, more researchers have published increasingly growing works over time. Some reviews among these researches have been conducted by Migdalas [1], Yang and H. Bell [2], Kepaptsoglou and Karlaftis [3], Farahani and Miandoabchi et al. [4], and recently by Xu and Chen et al. [5]. General network design or part of urban transportation network design has been

reviewed and summarized. And the latest review considered the transit and road network interplay, making a comparison of formulation approached as well as solution algorithm. However, as the problems are complicated and new research technology and challenges emerged, it is necessary to trace further research methods and results.

This paper attempts to present a systematic review of UTNDP according to the statistics data obtained from CiteSpace. To the best of our knowledge, few reviews of UTNDP have conducted reference analysis by the tool of CiteSpace to present the knowledge span map and to abstract the research clusters as the analysis focus. It is valuable for the following research directions. In particular, city logistics considerations, complex network research perspectives, and sustainability concerns are involved in the new trends.

Apart from reviewing UTNDP, we also summarize and compare the solution techniques, which provide the horizontal comparison for different types of problems, and demonstrate the efficient optimization directions.

The rest of the paper is organized as follows. Section 2 introduces data source and the analysis tool advantage. Section 3 explains analysis results as regards research focus and research font clusters based on CiteSpace. Highly cited references, author, and journal are also shown in this section. Section 4 mainly presents classifications of UTNDP problems and solutions. Section 5 focuses on different varieties of urban transportation network problem descriptions.

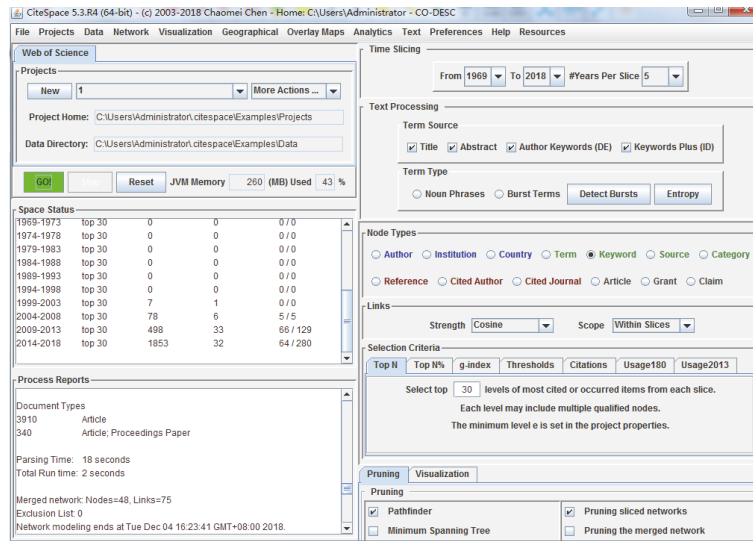


FIGURE 1: The original operation interface.

Section 6 depicts mathematical model for UENDP. Section 7 demonstrates solution methods to the problems. Ultimately, the possible following research concerns are demonstrated in Section 8 and conclusions are given in Section 9.

## 2. Data Source and Method

This article used CiteSpace [48] Visual analysis tools to draw various knowledge maps and Spectrum, showing research trends and hot trends in the field through elements such as node size, network connectivity, and key word co-occurrence. The visual tools used in this article are CiteSpace V Software, version is 5.3.R4 SE (64-bit). One of the core functions of this software is detection and analysis of the research frontier and knowledge relationship.

In order to ensure that the original data is comprehensive, accurate, and highly credible, this article chosen Web of Science as the data source, which is the largest global academic journal network. Dataset searched is about “urban transportation network design,” with the year period ranges from 1969 to 2018. Moreover, the category set as journal type and the nonacademic papers such as reports and proceedings have been deleted. As a result, 487 articles are selected for the research.

## 3. Knowledge Span Analysis

**3.1. Key Words Map.** Time zone segmentation is an important feature of CiteSpace software. It requires users to perform time zone segmentation (Time Slicing) to determine the length of a single time slice in order to perform timing capture on a knowledge domain and then connect these time-sharing pictures together to complete the subject knowledge mapping task from the perspective of diachronic research.

Currently, CiteSpace allows users to customize the size of the time interval to enhance the flexibility of the software application, but the appropriate and reasonable time interval

has no criteria. In general, the smaller the time interval, the greater the time sensitivity of the mapping is to reveal the evolution of knowledge in the field. But too small interval setting will result in a series of items difficult to be detected due to the small change range between the neighboring zones. As a result, the critical node would not be recognized.

Observation projects are not easy to be discovered because of the small variation in adjacent time zones, which in turn affect the identification of key nodes.

Firstly, a new project is set up and parameters are set as shown in Figure 1; preliminary operational results show that no data is found before 1998, so time range is reduced to achieve more accurate result.

The ultimate results and visualized graph are obtained after some adjusting of parameters as shown in Figure 2. The label clusters are formed by indexing items. The modularity is 0.5921, and mean silhouette is 0.4565. The map can display two or more natural network clusters, and there is a small amount of links between the clusters. Some of top frequencies of key words are presented in Table 1. At the same time, top 2 key words with the strongest citation bursts are design (3.0224) and ad hoc network (3.6875) as shown in Figure 4. The former burst begins with 2004 and ends with 2008, while the latter begins with 2012 and ends with 2014. It can be concluded that network design and advanced structure were and still are highly focused on. Six major clusters will be depicted further in the next section. With the purpose of comprehensive analysis, this paper visualizes another one key words clustering type as shown in Figure 3.

**3.2. Cocited References Map.** Here, reference is set as the node type and the same time slicing is set as that of key words. Apart from that, the threshold interpolation is used to choose the nodes constituting the network. C means the lowest citation frequencies; cc presents the lowest cocitation frequencies; ccv is the cocitation rate or co-occurrence rate between data. The following visualized map will be shown

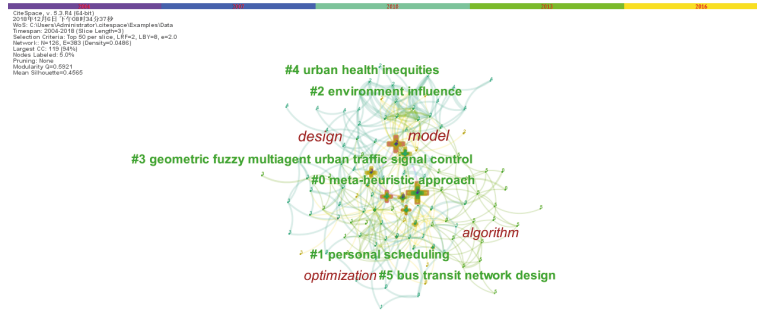


FIGURE 2: UTNDP key words clusters map case 1.

TABLE 1: Top frequencies of key words.

Freq.	Burst	Centrality	Sigma	Key word
110		0.1	1	model
97	3.02	0.25	1.97	design
69		0.23	1	optimization
65		0.08	1	algorithm
63		0.08	1	transportation
62		0.09	1	network
60		0.12	1	system
41		0.03	1	genetic algorithm
37		0.06	1	network design
29		0.01	1	transportation network
25		0.09	1	demand
25		0.04	1	equilibrium
24		0.03	1	land use
24		0.01	1	road network
24		0.12	1	management
22		0.1	1	network design problem
21		0.01	1	walking
20		0.02	1	physical activity
19		0.07	1	congestion
19		0.16	1	impact
18		0.02	1	city
17		0.07	1	time
16		0.07	1	built environment
16		0.04	1	design problem
15		0.04	1	behavior
15		0.05	1	intelligent transportation system
15		0.03	1	urban form
13		0.02	1	capacity
13		0	1	performance
13		0.01	1	sustainability

after clustering, adjusting, and burst detecting, and Figure 5 and Table 2 showed the cocitation network. Only four reference citation bursts are found as given in Figure 6. In this case, modularity is 0.8301, and mean silhouette is 0.5451, so the clustering effect is coordinated with the requirements. Some highly cited references are listed in Table 2. Citations with the strongest burst are given in Figure 6. Such clusters as bilevel

programming, modes, chance constraint, and macroscopic fundamental diagram are outstanding. Mathematical models for UTNDP are proved to be the research mainstream. Bilevel programming or leader-follower problem is usually viewed as the common formulation for the problem. Systematic review for this formulation will be presented in the next section.

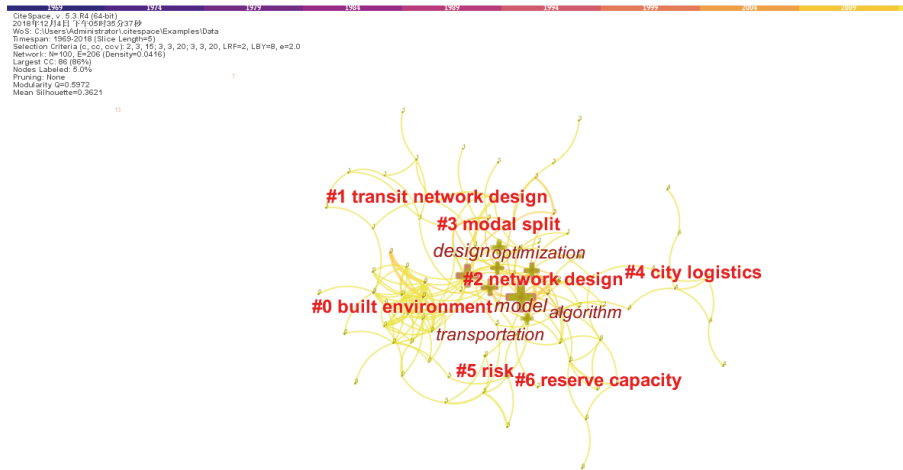


FIGURE 3: UTNDP key words clusters map case 2.

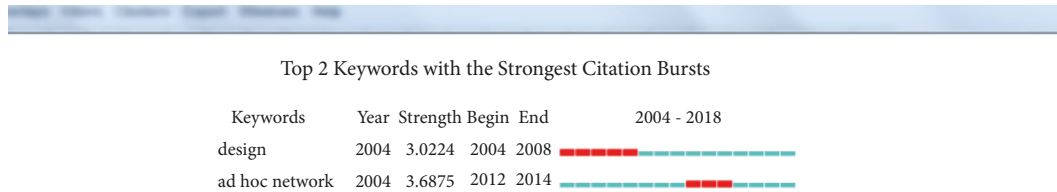


FIGURE 4: Key words with the strongest citation bursts.

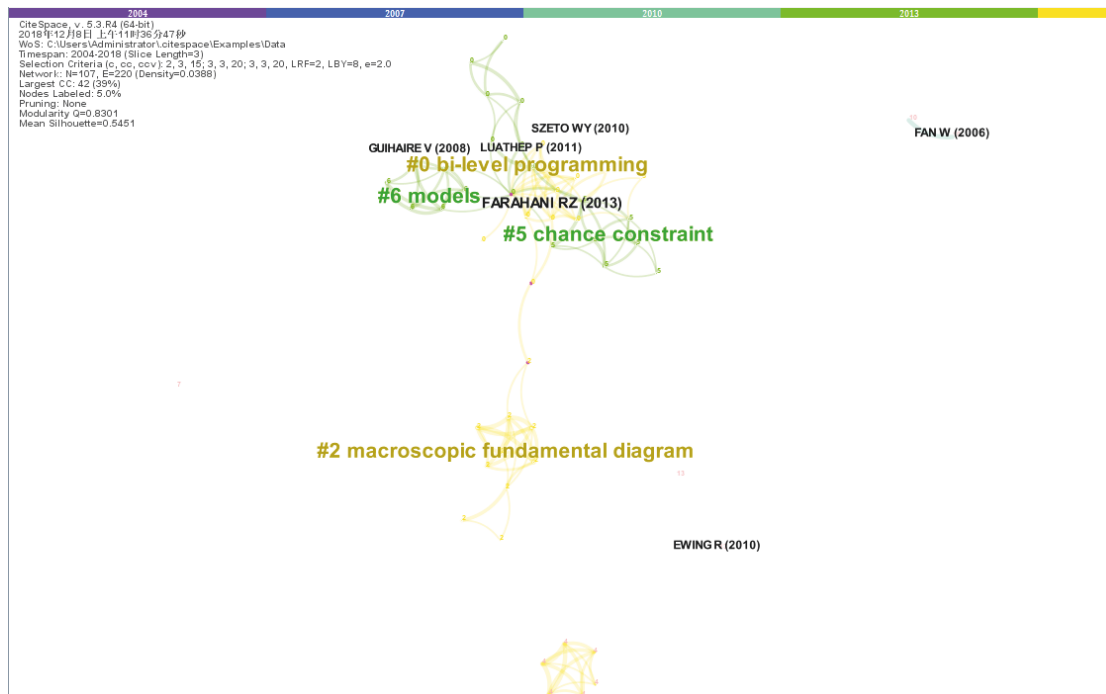


FIGURE 5: Cocitation network map.

3.3. *Cocited Journals Map.* This part mainly presents journals with highly cocited rate in UTNDP research. Journals are important carrier of professional academic knowledge dissemination. Bibliometric information metrology usually

uses impact factors, citation frequency, and other indicators to characterize the role of journals in academic exchanges. In fact, the basis for the citation of journals is the mutual citation and citation relationship between journals. The relationship

TABLE 2: Top frequency Cocitation references.

Freq.	Burst	Centrality	Author	Source	Half-life	Cluster ID
20		0.12	Farahani RZ	EUR J OPER RES	4	0
12		0.03	Luathep P	TRANSPORT RES B-METH	5	0
10	4.56	0.02	Guihaire V	TRANSPORT RES A-POL	7	6
10	3.76	0	Fan W	J TRANSP ENG-ASCE	6	10
10		0	Ewing R	J AM PLANN ASSOC	8	13
10		0.07	Szeto WY	COMPUT-AIDED CIV INF	5	5
8		0.01	Yim KKW	TRANSPORT RES C-EMER	5	5
8		0.08	Szeto WY	NETW SPAT ECON	2	0
7		0.01	Liu HX	TRANSPORT RES B-METH	1	0
7		0.04	Ji YX	TRANSPORT RES B-METH	5	2
6		0	Niu HM	TRANSPORT RES C-EMER	4	4
6	2.86	0	Li ZC	INT J SUSTAIN TRANSP	2	5
6		0	Szeto WY	COMPUT-AIDED CIV INF	4	0
6		0	Barrena E	TRANSPORT RES B-METH	3	4
6		0	Wang DZW	TRANSPORT RES B-METH	7	0
6		0	Mazlounian A	PHILOS T R SOC A	7	2
6		0.04	Sharma S	ENVIRON PLANN B	7	0
6		0.04	Ramezani M	TRANSPORT RES B-METH	2	2
6		0	Szeto WY	EUR J OPER RES	6	0
6		0	Niu HM	TRANSPORT RES B-METH	2	4
5		0	Geroliminis N	TRANSPORT RES B-METH	6	2
5		0	Kepaptsoglou K	J TRANSP ENG	6	6
5		0.11	Wu D	TRANSPORT RES B-METH	4	0
5		0	Mauttone A	COMPUT OPER RES	6	6
5		0	Lozano S	EUR J OPER RES	5	7
5		0	Cacchiani V	TRANSPORT RES B-METH	2	4
5		0	Willumsen LG	MODELLING TRANSPORT	7	13
5		0	Long JC	EUR J OPER RES	4	0
5		0.03	Geroliminis N	TRANSPORT RES B-METH	8	2
5		0	Gayah VV	TRANSPORT RES B-METH	6	2
5		0	Miandoabchi E	CENT EUR J OPER RES	2	5
5		0.1	de Palma A	TRANSPORT RES C-EMER	7	2
5		0	Canca D	J ADV TRANSPORT	4	4
5	2.92	0	Yin YF	TRANSPORT RES D-TR E	8	5
5		0.02	Cipriani E	TRANSPORT RES C-EMER	3	6

Top 4 References with the Strongest Citation Bursts



FIGURE 6: References with the strongest citation bursts.

between the two journals can also be expressed by the cocitation of other journals. The higher the frequency is, the closer the relationship is, which means that the closer the disciplines of the two journals are, the more the various journals without external connections are smoothly linked

to reveal the interrelationship between certain disciplines. The software based on the same database gives the following conclusions on cocited journals clustering as shown in Figure 7, which is generated after classifying all of the original cocited journal data; some of cocited journals with



FIGURE 7: Cocited journals clustering map.

top frequency were demonstrated in Table 3. What is more, Figure 8 presents top 24 cited journals with the strongest citation bursts.

**3.4. Cocited Authors Map.** The author's cocitation analysis has become a potentially prolific analytical method, which can be used not only to reveal the development status and even the changes of the scientific structure, but also for frontier analysis, domain analysis, scientific evaluation, etc. This paper conducts the cocited authors analysis and visualized map and name lists are presented in Figure 9 and Table 4. What is more, 13 cited authors have the strongest citation bursts, as demonstrated in Figure 10. Most of clusters in this part are mainly concerned about bus transit network design and urban traffic control structure. The colors of clusters labels are coordinated with time slice colors. Specially, cluster 8 gives some evidence that small network or complex network recently attracting more distinguished researcher's interests. That means the importance of complex network in the area of UTNDP.

#### 4. Classifications of UTNDP Problems and Solutions

According to Section 3, research clusters have been drawn as simply merged in Table 5. This paper attempts to classify these clusters in terms of problems, models, and solutions. With regard to the problems, bus transit network design has been the research focus among UTNDPs. At the same time, more and more UTNDP problems take consideration of environment influence from the view of sustainability. With

the e-commerce development and "New Retail" emergence, city logistics has been an essential consideration during the urban transportation network designing process. Also, some study has shown urban traffic flow networks existence macroscopic fundamental diagram. Most of urban traffic network has demonstrated the properties of small work. Quite a few researchers concentrated on complexity and robustness of urban transportation network.

As for the models of UTNDP, bilevel programming is the most common formulation. Some lower-level problem is formulated as the modal split traffic assignment. Personal scheduling and urban health inequities are concerned about in traffic assignment as well. Reserve capacity is proposed as upper-level problem optimization objective to avoid paradox proposed by Hai and Bell [7].

For solutions of UTNDP, the cluster classifications reveal that metaheuristic, the product of random algorithm combined with local algorithm, has been the mostly used approach.

#### 5. Review of Urban Transportation Network Problem

**5.1. Definition of UTNDP.** UTNDP mainly concentrates on existing street capacity expansion or building new streets [49]; it can be divided into Road Network Design Problem (RNDP), Transit Network Design Problem (TNDPs), and Multimodal Network Design Problem (MMNDP). Decision making of transportation planning deals with strategic, tactical, and operational level and tactical level and strategic level decision. Strategic decisions refer to long-term decisions on

TABLE 3: Cocited Journals with top frequencies.

Freq.	Burst	Centrality	Year	Source	Half-life	Cluster ID
238		0.32	2004	TRANSPORT RES B-METH	12	0
206		0.06	2005	TRANSPORT RES REC	10	0
186		0.14	2006	TRANSPORT RES A-POL	10	0
182		0.03	2004	TRANSPORT RES C-EMER	12	0
168		0.32	2004	EUR J OPER RES	11	1
168		0.11	2005	TRANSPORT SCI	10	1
108		0.13	2005	J TRANSP ENG-ASCE	10	0
94		0	2010	TRANSPORT REV	6	0
92		0.24	2010	TRANSPORT RES D-TR E	6	3
91		0.11	2010	IEEE T INTELL TRANSP	6	5
89		0.1	2010	COMPUT OPER RES	5	1
85		0.05	2010	TRANSPORTATION	6	2
80		0	2010	TRANSPORT RES E-LOG	6	0
78		0.03	2011	NETW SPAT ECON	5	0
76		0.05	2010	TRANSPORT POLICY	6	2
72		0.01	2010	TRANSP RES RECORD	5	0
65		0.01	2004	OPER RES	11	1
65		0	2010	COMPUT-AIDED CIV INF	6	0
64		0	2010	J ADV TRANSPORT	6	0
55		0.06	2013	J TRANSP GEOGR	3	2
55		0.13	2005	URBAN TRANSPORTATION	10	2
52	8.49	0	2016	THESIS	1	0
51		0	2010	LECT NOTES COMPUT SC	5	4
49		0.07	2010	J AM PLANN ASSOC	6	3
47		0.19	2010	ENVIRON PLANN B	6	2
43		0	2010	MANAGE SCI	5	1
43		0	2010	J OPER RES SOC	5	1
43		0.03	2010	ANN OPER RES	5	1
42		0	2013	EXPERT SYST APPL	4	4
41		0	2013	PROCD SOC BEHV	3	1
40		0.01	2010	Transportation Science	5	1

the transportation network infrastructures. Tactical decisions mean to effectively utilize the existing infrastructures and resources of the network, and operational decisions focus on short-term decisions, mainly covering traffic flow control and demand management. Table 6 shows cases and features of three-level decisions.

*5.2. Road Network Design Problem.* RNDP usually concentrates on street networks and deals with private and public transit vehicles at the same time. RNDP traditionally considers all traffic flows as the same kind of flow. RNDP arises when policy maker seeks to optimizing the features of the road network. The inputs, variables, and constraints formulated in RNDP are listed in Table 7

Urban road network design problems are normally classified as Continuous Network Design Problem (CNDP), Discrete Network Design Problem (DNDP), and Mixed Network Design Problem (MNDP) as well; Table 8 provides the details.

Recently, a large number of UTNDP researches focus on DNDP; Miandoabchi and Farahani et al.'s work [21] concerns DNDP with bimodal and biobjective, where consumer surplus maximizing and bus mode share maximizing are set as decision objective. This formulation covers such common discrete decision variables as new street building, lane addition, lane allocation, and two-way streets converted to one-way street. Particularly, exclusive bus lanes consideration is added as a special and important variable. Thus, modal-split/assignment model in the lower level deterministic user equilibrium, in this case, is adopted to obtain the bus and auto flows. At the same time, Miandoabchi and Daneshzand et al. [22] address a multiobjective decision on designing road network, with the attempt to optimize the new travel and reserve capacity of the network. The formulation of this problem is mixed-integer programming. The author makes use of a hybrid Genetic Algorithm (GA), a Simulated Annealing (SA) after evolution, and a hybrid Artificial Bee Colony algorithm (ABC) as well for solution. Long and Szeto et al. [24] consider a biobjective turning restriction design

Cited Journals	Year	Strength	Begin	End	2004 - 2018
TRAFFIC ENG CONTROL	2004	3.1797	2004	2015	[Timeline: 2004-2015]
NETWORKS	2004	4.1416	2010	2015	[Timeline: 2010-2015]
MATH COMPUT MODEL	2004	4.0427	2010	2014	[Timeline: 2010-2014]
TRANSPORTATION RES B	2004	4.1416	2010	2015	[Timeline: 2010-2015]
J COMPUT CIVIL ENG	2004	2.9181	2010	2015	[Timeline: 2010-2015]
PREV MED	2004	3.3165	2010	2012	[Timeline: 2010-2012]
J URBAN PLAN D-ASCE	2004	3.6516	2010	2015	[Timeline: 2010-2015]
STUDIES EC TRANSPORT	2004	3.3165	2010	2012	[Timeline: 2010-2012]
TRANSPORT RES	2004	5.6974	2011	2015	[Timeline: 2011-2015]
ACCIDENT ANAL PREV	2004	3.8807	2011	2015	[Timeline: 2011-2015]
J REGIONAL SCI	2004	2.9313	2011	2012	[Timeline: 2011-2012]
TRANSPORTATION NETWO	2004	4.1002	2012	2014	[Timeline: 2012-2014]
TECHNICAL REPORT	2004	4.6267	2013	2015	[Timeline: 2013-2015]
TRANSPORTMETRICA	2004	5.0142	2013	2015	[Timeline: 2013-2015]
J HEURISTICS	2004	3.0798	2013	2015	[Timeline: 2013-2015]
ADV ENG SOFTW	2004	3.8526	2013	2015	[Timeline: 2013-2015]
ENG OPTIMIZ	2004	3.4661	2013	2015	[Timeline: 2013-2015]
IEEE INT C INTELL TR	2004	3.0798	2013	2015	[Timeline: 2013-2015]
J INFRASTRUCT SYST	2004	3.0798	2013	2015	[Timeline: 2013-2015]
J E ASIA SOC TRANSP	2004	4.2395	2013	2015	[Timeline: 2013-2015]
THESIS	2004	8.4881	2016	2018	[Timeline: 2016-2018]
TRANSPORT PLAN TECHN	2004	2.9037	2016	2018	[Timeline: 2016-2018]
NATURE	2004	3.0661	2016	2018	[Timeline: 2016-2018]
TRANSPORTMETRICA A	2004	3.2286	2016	2018	[Timeline: 2016-2018]

FIGURE 8: Top 24 cited journals with the strongest citation bursts.

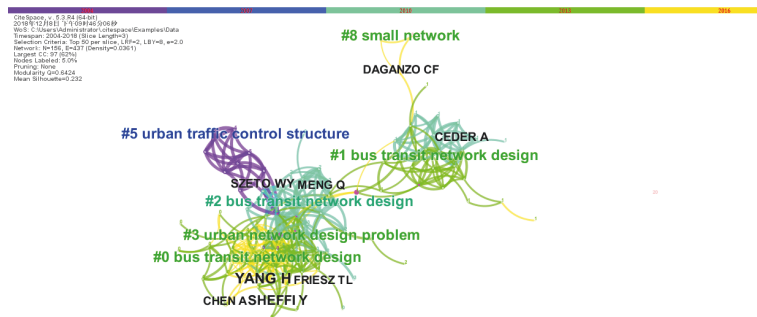


FIGURE 9: Cocited authors' visualization map.

problem, whose purpose attempts not only to reduce the travel time, but also to reduce environmental pollution. The authors developed heuristic modified artificial bee colony, and in the end, Pareto optimal turning restriction strategies are found.

Furthermore, Long and Gao et al. [19] focus on turning restrictions in the urban road network. The problem is formulated as bilevel programming. Minimization of total

travel cost is the upper-level decision, while lower level one concerns the travelers' route choice according to stochastic user equilibrium (SUE). As for the optimal solution, sensitivity analysis algorithm is carried out first, then branch and bound method is taken to solve the problem.

Miandoabchi and Farahani [20] design the urban road network from the perspective of reserve capacity maximization. It mainly focuses on lane addition optimum decision,



TABLE 4: Authors with high Cocitation frequency.

Freq.	Centrality	Sigma	Author	Year	Half-life	Cluster ID
74	0.02	1	Yang H	2006	9	0
52	0.03	1	Sheffi Y	2005	9	0
38	0.04	1	Szeto WY	2013	3	0
34	0.02	1	Ceder A	2010	5	1
33	0.07	1	Friesz TL	2005	10	0
33	0.03	1	Daganzo CF	2010	6	8
32	0.01	1	Chen A	2011	4	0
32	0.24	1	Meng Q	2010	5	0
29	0.01	1	Yin YF	2013	3	0
29	0	1	Cervero R	2013	3	4
29	0.02	1	Lo HK	2012	3	0
27	0.02	1	Nagurney A	2011	5	2
26	0.1	1	Magnanti TL	2010	5	0
26	0	1	Ewing R	2013	5	4
24	0.04	1	Li ZC	2014	2	0
22	0.01	1	Farahani RZ	2014	3	0
21	0	1	Frank LD	2010	8	4
20	0	1	Ukkusuri SV	2010	6	3
19	0.02	1	Wardrop JG	2013	4	0
18	0.06	1	Newell GF	2010	5	1
18	0	1	Bell MGH	2013	3	0
18	0.02	1.05	Gao ZY	2010	4	3
18	0.03	1	Miandoabchi E	2013	3	0
18	0.01	1	Zhao F	2010	6	1
17	0.02	1	Laporte G	2013	3	1
17	0.01	1	Fan W	2010	4	1
17	0.01	1	Baaj MH	2010	4	1
16	0.01	1	Sumalee A	2013	3	0
16	0	1	Lam WHK	2013	3	0
16	0	1	Saelens BE	2010	8	4
16	0	1	Crainic TG	2014	2	1
16	0	1	Zhang L	2013	3	25
16	0.01	1	Luathep P	2013	3	0
16	0	1	Litman T	2013	4	40
15	0	1	Geroliminis N	2013	3	8
15	0	1	Huang HJ	2014	2	0

two-way street lane allocations, and street directions configuration design. The problem is formulated as bilevel programming as well. An evolutionary SA and hybrid GA are proposed for the solution.

Jiang and Szeto [25] incorporate health impacts into the time-dependent DNDP of RNDP. In the bilevel optimization, network expansion related factors are taken into consideration, involving accidents, gas emission, and noise. The authors put forward ABC algorithm for solution. On the other hand, successive averages and the Frank-Wolfe algorithm are selected for the lower-level solution.

Wang and Meng et al. [23] focus on DNDP involving multiple capacity levels and formulate the problem as bilevel programming. Minimization of total travel time and

traditional UE are separately set as upper-level objective and lower-level traffic assignment. UE reduction and system optimal relaxation are put forward as global optimization methods.

With regard to road network layout, Galloabb [18] proposes a nonlinear constrained optimization model and Scatter Search (SS), a metaheuristic algorithm, and makes an effort to design intersections signal parameter and set existing road direction.

For CNDP, Palma and Lindsey [50] review the roads congestion pricing problem and make a comparison between different methods and technologies. Liu and Wang [26] investigate CNDP by means of improving capacity. The flow of network is stochastic user equilibrium. The paper

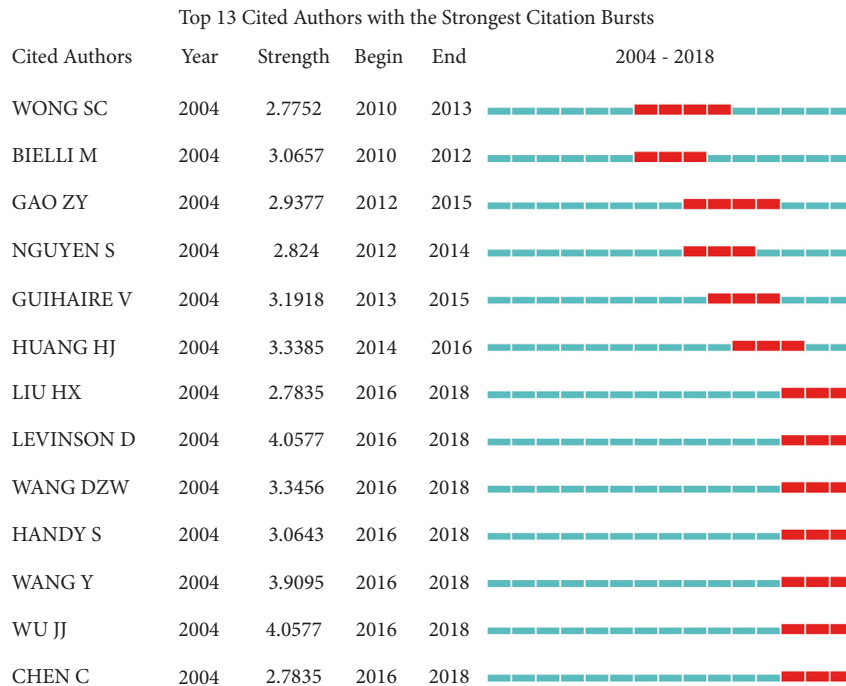


FIGURE 10: Strongest citation bursts for cited authors.

transforms the nonlinear nonconvex programming problem into a nonlinear convex program.

As for MNDP, bilevel formulation is still applicable. Szeto and Jiang et al. [27] put forward such a model for MMNDP. Road link direction redesigning, road capacity expansion, and intersections signal settings are for the upper level aiming at reserving capacity optimization. Traffic assignment by UE method is for the lower level. Golden section search, integrated with Scatter Search method, was evolved for optimal solution.

Cantarellaabb [51] concentrates on checking out various algorithm performances; that is, how well does the topology design behavior after these algorithm optimizations. The application to real networks demonstrates the strength and weakness of these algorithms. What is more, algorithms' efficiency is provided.

**5.3. Transit Network Design Problems.** Transit transport service, viewed as the important contribution to sustainable urban development, has been in an effort to enhance traffic supply and offer good service. Practically, due to decision time zone and function, Transit Network Planning Problem (TNDP) is normally divided into the three dimensions: strategical, tactical, and operational ones [4, 52]. Each decision level plays a role in efficiency of the system. The efficient transit system not only directly reduces environmental impact, examples are cutting down fuel consumption, pollutants, and noise, but also supports individual transportation mode interaction and connection. When it comes to strategical level, multilevel, wide-cover public transport network and service system are the main considerations. As far as tactical planning decisions are concerned, they

include timetabling problem, frequency setting problem, and design of operational strategies. The main objective of tactical decisions is to coordinate different transport modes to meet specific demand, to minimize waiting time, or to promote synchronization project or event. For operational planning decisions, researchers pay attention to driver rostering or scheduling and vehicle scheduling problem as well. Furthermore, transit network design belongs to the UTNDP. It can be classified as two types as well: continuous and discrete transit network design.

**5.4. Multimodal Network Design Problem.** Multimodal network system is defined as the combination system, where information transportation system connected all traveler modes and kinds of transportation systems. Millions of travel modes, travelers, and network infrastructures are included in the large cross system. Travel modes range from automobile and motorcycle to subway, bus, and even walk.

Bielliabb [53] is concerned with object model for network and multimodal shortest path algorithm. It implements and tests a resolution to the long-run transit network planning. The work offers a method to find out the facilities nodes in the network which uses different travel modes.

Geroliminis and Nan et al. [54] firstly investigate the role of aggregated relationships in describing the performance of urban multimodal network, in which buses and automobiles share the identical road infrastructure. Next, the paper puts forward a 3-dimensional vehicle Macroscopic Fundamental Diagram (MFD) regarding the accumulation of cars and buses and develops the total circulating vehicle flow in the urban transportation network. Then, with the attempt to access the 3-dimensional MFD, the authors put forward to

TABLE 5: Cluster Classification.

Cluster standard	Cluster type
Key words clusters (case 1)	#0 meta-heuristic approach (s); #1 personal scheduling; #2 environment influence; #3 geometric fuzzy multi-agents urban traffic signal control; #4 urban health inequities; #5 bus transit network design;
Key words clusters (case 2)	#1 transit network design; #2 network design; #3 modal split (lower level); #4 city logistics; #5 risk; #6 reserve capacity;
Cocitation network clusters	#0 bi-level programming; #2 macroscopic fundamental diagram; #5 chance constraint; #6 models;
Cocited journals clusters	#0 urban network design problem; #1 urban network design problem; #2 environment influence; #3 environment influence; #4 evolutionary solutions; #5 urban traffic management; #6 vehicle information sharing network;
Cocited authors clusters	#0 bus transit network design; #1 bus transit network design; #2 bus transit network design; #3 urban network design problem; #5 urban traffic control structure #8 small network

demonstrate the flow characteristics in bimodal network. The problem is solved by partitioning algorithm, by which the network is classified into a small number of areas sharing the same characteristics.

Jin and Tang et al. [55] introduce a metro-bus network to enhance the metro network resilience to disruptions through integrating with bus services. They put forward a two-stage stochastic programming formulation for evaluating the intrinsic metro network robustness. The metro local connection with bus services is optimized as well.

Chiabaut and Xie et al. [56] analyze various urban multimodal arterial performances. Comparisons are made between when there are only bus lanes and when the automobiles and buses are being used in the same road. An aggregated and simple model is used to explain the congested traffic and free-flow case. The values of multimodal traffic dynamic on the arterial roads are analyzed.

Song and Yin et al. [57] put forward a simulation-based systematic model to access and optimize the sustainable and efficient operation of multimodal transportation systems. The

optimization aims at obtaining an optimal planning and operation combination. The method is applied to Tianjin Eco-City network with multimodal travelers. And the results present that the approach is applicable and feasible.

*5.5. City Logistics.* With the quick development of electronic commerce and frequently daily delivery services enhancement, city logistics need to get improved and meet the challenges and deal with the last-mile parcel delivery. For a lot of cities around the world, a serious congestion and environment problem is caused by freight vehicles within city logistics. At the same time, the pollutant emissions of the freight vehicles are very high. What is more, urban logistics cost, especially transportation costs, occupied a large portion of the operating costs of many firms. As a result, urban network design research has to consider the routing and schedules of freight vehicles.

Some research considered the integration of freight and passenger transportation making use of shared vehicles.

TABLE 6: UTNDP decision level.

Decision level	Features	Examples
Strategic	Long-term, focus on new infrastructure building	(1) Building new streets; (2) designing bus routes; (3) expanding existing streets
Tactical	Mid-term, focus on improving existing performance of resources	(1) Determining the orientation of one-way streets; (2) allocating exclusive bus lanes; (3) determining the allocation of lanes in two-way streets
Operational	Short-term, focus on traffic flow and demand management	(1) Determining transit service frequency; (2) scheduling traffic lights; (3) determining transit schedule; (4) scheduling of repairs on urban streets

TABLE 7: Formulations of RNDP.

Input	(1) The travel demand of OD pair; (2) the network topology; (3) the streets characteristics covering lanes number, capacity, travel time specifications, and travel time of free flow; (4) decision variables bound both or lower and upper level, examples are maximum toll level or maximum capacity increase (5) the available budget; (6) each single project cost; (7) candidate network improvement projects
Decision variables	(1) Topological variables: street capacity expansion; directions of links; new street construction; one-way street consideration; (2) parking variables: parking allowed or not; (3) fare variables: parking or road pricing; (4) signal setting variables: green times ratio, cycle length, phase plan of signalized intersections, turning restrictions at intersections
Constraints	(1) The budget constraint; (2) cycle time constraints; (3) capacity constraint; (4) lower and upper bound constraints;
Decision objective	(1) Reserve capacity maximization; (2) consumer surplus maximization; (3) travel cost minimization; (4) construction cost minimization (5) total vehicle miles' minimization; (6) total travel distances minimization; (7) total societal cost minimization;

TABLE 8: RNDP decisions classifications.

Type	Design decisions
DNDP	Discrete design decisions: (1) Adding new lanes; (2) constructing new roads; (3) determining intersections turning restrictions; (4) determining one-way street direction
CNDP	Continuous design decisions: (1) Traffic lights scheduling; (2) street capacity expansion; (3) specific streets' toll decision;
MNDP	A combination of CNDP and DNDP

Reference [58] proposed a mixed-integer linear programming formulation and compared mixed-purpose and single-purpose vehicles in terms of 216 transportation scenarios. Furthermore, Fatnassi and Chaouachi et al. [59] investigated the common features of rapid transit both for passenger and cargo; accordingly, they put forward an effective network design resolution to improve city logistics sustainability.

Ewedairo and Chhetri et al. [60] made use of spatial dimensions describing road network features and then weighed the possible road network resistance or difficulty to last-mile delivery. The work devised localized strategies and helped to mitigate the last-mile deliveries possible delay. Köster and Ulmer et al. [61] have chosen courier express and parcel services as the research object and planned efficient routing for them to enhance fast and reliable services at reasonable prices.

With the purpose of reducing pollutant emissions, Behnke and Kirschstein et al. [62] formulated a vehicle routing problem to minimize emission and improve the effects of path selection in UTNDP. In reality, multiple paths consideration in urban network design is able to decrease a large number of emissions. Sun and Duan et al. [63] provided vehicle routing problem solution for large-scale urban transportation networks without increase in freight cost and environmental impacts.

Crainic and Errico et al. [64] put forward a stochastic programming with two stages. In stage 1, the service network is selected and general capacity is determined. In stage 2, vehicle routing on the second tier is considered. Crainic and Sgalambro [65] also concentrated on a two-tier city logistics systems. The paper puts forward a model which planned service network design generally. Görçün [66] mainly solved the insufficient connections between different logistics nodes, taking into account the logistics nodes relationships, capacities, and logistics system performance.

Some studies focus on impacts of location on congestion and gas emissions. Reference [67] put forward methods to locate the facility with high logistics demand, taking both emission and congestion into consideration. Tabu Search and memetic algorithms were developed and tested with a conventional genetic algorithm.

You and Chow et al. [68] solved the sequential selective vehicle routing problem considering constraints on temporal

space first and then calibrated the model with feasible method and accessible data that can be easily observed to improve economic and environmental sustainability.

## 6. Mathematical Model for UTNDP

6.1. *Bilevel Problem in UTNDP.* Bilevel programming is a normally used tool for UTNDP. It is also called as leader-follower problem. Decision-makers' or leaders' problem corresponds to upper level, with leaders designing and planning the transport network. For this level, policy consideration in practice, decision objective, and restrictions will be made. On the other hand, traveler's or follower's problem is named as the lower level problem, whose decision is to decide whether to go and which mode or route to choose. In this model, the travelers are not offered the opportunity to estimate in advance the decision-maker's policy and plan, but only are permitted to take selection after getting knowledge about the leader's decision. The following mathematical model is normally used to depict the problem:

$$(UO) \min_u F(u, v(u)) \tag{1}$$

$$s.t. \quad G(u, v(u)) \leq 0 \tag{2}$$

where  $v(u)$  is implicitly determined by

$$(LO) \min_v f(u, v) \tag{3}$$

$$s.t. \quad g(u, v) \leq 0 \tag{4}$$

For upper-level problem,  $U$  means decision variable vector,  $F$  represents objective function, and  $G$  is vector function of constraint. For lower-level problem,  $u$  means and decision variable vector, while  $f$  refers to objective function and  $g$  is the vector function of constraint.

$v(u)$  is the reaction of response function, showing the user reaction on traffic assignment for specific network designing  $u$ .  $v(u)$ , as an implicit function, is described by LO and cannot be shown explicitly. In the NDP,  $v(u)$  is an optimal solution of LO. Essentially, for bilevel network design problem, it aims at getting the optimal decision vector  $u$  to optimize the objective function  $F$ , subject to the network design constraint as well as the user reaction constraints (3) and (4).

To simplify the solution, the bilevel problem NDP is usually formulated as the equilibrium-constrained mathematical program if lower-level problem is described to be a variation inequality. Thus, UTNDP is changed into single-level problem. However, as far as the concept concerned, it is bilevel essentially and involves two different classes of games, either the noncooperative Nash game or the leader-follower game.

It is difficult to solve a bilevel programming with accurate resolution tools due to the NP-hard problem. Boyce [69] studied bilevel problems and drawn the conclusion that even a simple bilevel problem with both linear upper-level and lower-level problems is also NP-hard[4]. What is more, no convexity of bilevel problems leads to the solution difficulties. Suppose the upper- and lower-level problems show the convexity feature, the problems cannot be guaranteed to be convex [70].

*6.1.1. Upper-Level Problems in UTNDP.* There are traditionally two kinds of UTNDP, namely, RNDP and TNDSP. And there are three subtypes of RNDP: (1) Discrete Network Design Problem (DNDP), where decisions are discrete type; examples are new lane adding, new road construction, one-way streets direction setting, and turning restrictions setting, (2) Continuous Network Design Problem (CNDP), which considers continuous decisions; examples are street capacity expansion, traffic lights time setting, and tolls setting for specific streets, and (3) Mixed Network Design Problem (MNDP), which combines continuous and discrete decisions.

TNDSP mainly focus on the topology of the public transit network, service frequency, and timetables. There are five subtypes for TNDSP in terms of decisions: (1) transit lines design; (2) the service distribution and rate of each bus line besides route design, namely, the Transit Network Design and Frequency Setting Problem (TNDSP); (3) frequency setting given the route structure; (4) the timetables based on service frequency and routes; and (5) both the scheduling for time and frequency according to the given line setting.

MMNDP is the third category, in which multiple modes are covered and their demand are interrelated. If only there are two different modes in UTNDP, it will be classified as MMNDP. Traffic flow in MMNDP may encompass a wide variety of patterns whether it is motor or nonmotor vehicle, aboveground or underground. Bimodal programming is the special situation of MMNDP. With more consideration and simulation of two modes in network design, multimodal problem arises. Decisions involved in MMNDP can be comprehensive, covering various decisions for various modes, and can only be related to one mode. The flows of different modes could have interactions or not, and decisions may have relations with the flow. When automobiles run on the identical routes with buses, the bus flow has an impact on the other and vice versa.

*6.1.2. Lower-Level Problems in UTNDP.* On the contrary, this kind of problem can be described in different forms due to the choice dimension and the assumptions used by the travelers. There exist some different lower-level problems between RNDP and TNDP. The former takes vehicles as flow

units, while the latter views passengers as flow units. Most of the lower-level problem considers trip allocation issue. Road network, as well as transit network, separately has different considerations on trip allocation classes; these allocations program on transit or traffic will have effects on the flow form.

Trip assignment normally takes into account some behavioral principles to describe the route decision. Wardrop's principle is traditionally adopted; it means the users pick the shortest route as their choice. It is assumed that there exists no cooperation among different users; at the same time, the users are aware of each route they picked and the travel time generated. Parking cost and toll consideration could also make use of the extension of Wardrop's principle. User-equilibrium assignment (UE) is the pattern of flow; assumptions are that users do not have any attempt to change their route choice. In this situation, the users would take a longer time to finish their trip. The UE allocation can be extended to stochastic user equilibrium (SUE) assignment. On the contrary, SUE considers there is possibility that users have no knowledge of their trip hour exactly, so the selection is based on perceiving.

Some research considered congestion effect in traffic assignment problems. Thus, it contributes to congested and uncongested assignment. Given there is no congestion and the flow allocation following the Wardrop's principle, the flow allocation problem is transformed into all-or-nothing issue; that means the shortest route will be full of overall travel request. What is more, suppose the assumption has been changed into SUE, the case becomes stochastic uncongested allocation.

The transit assignment also has two different types, with one considering the congestion and the other considering the free flow. As for free-flow traffic, passenger capacity has not been taken into consideration. It is not the case for congestion traffic. So these two problems consider different criteria and passenger behaviors.

If there exists more than one trip choice faced by users, simultaneously, the users have other references, the problem is transformed into trip distribution-allocation one. Specially, for MMNDP, given that both mode and route are considered, it becomes modal split-traffic assignment type. Furthermore, more complicated travel choice problem occurred for the traffic assignment because more complicated and various factors need to be considered. Users will integrate transportation mode, final destination, and decision to travel or not together.

On the other hand, demand between each OD can vary or keep unchanged. Traditionally, demand is viewed as fixed or unchanged. On the contrary, if the demand varies by travel time or other system factors, it becomes elastic. Elastic demand has two forms: either every OD pair demand is elastic or total demand is unchanged, while each mode allocation is variable. MMNDP usually concerns with the latter scenario.

*6.2. Macroscopic Fundamental Diagram.* As people's research on traffic congestion problems shifts from isolated points to the basic unit of the community, and finally to the entire network, people continue to research and find that cities' flows normally show the existence of Macroscopic

Fundamental Diagram (MFD). Daganzo and Geroliminis [71] and Geroliminis and Daganzo [72] proposed the concept of MFD and gave a descriptive definition of MFD in the subsequent research, which is considered to describe moving vehicles number has certain relations with network operation level. At the same time, there exist some relations between the network weighted traffic and the network traffic volume. Thirdly, distance traveled to the entire road network and the time spent have interaction relations as well. This definition was further refined in subsequent studies. Daganzo believes that this means a lot for traffic planning and management; the MFD can also be used to describe the relationship between the flow output and vehicles number of the region; what is more, the traffic flow and traffic density has interaction relation or the vehicle's mileage and vehicle runtimes.

After that, research around the MFD is also constantly evolving. Relevant researches mainly focus on the existence, shape, applicable conditions, influencing factors, and application direction of MFD for verification and research.

Daganzo and Geroliminis [71] discovered a MFD with regard to average flow and average density, which has blocks of diverse lengths and widths. It also offers the exact analytical expressions in terms of streets' capacity and streets' MFD based on the shortest path.

Geroliminis and Daganzo [72] conducted a field experiment in Yokohama; the experiment revealed that an MFD existed on a large urban area. The MFD links density, space-mean, and speed. The sensors used in the experiment are detectors established unmoved and probes established on the floating vehicle. The value of MFD existence is to easily measure the trip completion rates as it reveals a confirmed and stable relation between the space-mean flows in the overall urban transportation system.

Daganzo [79] presents the clockwise loops in the MFD. It used the two-bin model and find out that with the density decreased, networks were easily to change, while the change was not as sharp as that when density increases. The instability contributes to clockwise hysteresis loops to appearing in MFD of the network. If unpredicted demand was distributed to origin or destination points, it might give rise to the hysteresis loops.

Following the existence of MFD for urban traffic, Geroliminis and Sun [73] investigated the condition when an urban traffic network needs to satisfy so that an MFD with low scatter exists. Vehicle density distribution in space was proved to have an impact on the MFD scatter and diagram form. Congestion distribution in space was put forward after the process of analysis and derivation. The MFD scatters in terms of errors in the probability density function of spatial link occupancy and errors of individual links' fundamental diagram. In the end, the authors used real data on urban main street and a freeway network to validate the proposed derivations and found that an MFD was not well defined in freeway networks.

Geroliminis and Nan et al. [54] further developed a vehicle MFD from three dimensions and investigated if aggregated relationships can describe the performance of urban bimodal networks with buses and cars sharing the same road infrastructure and identify how this performance

was influenced by the interactions between modes and the effect of bus stops. A parsimonious model was put forward to describe the bimodal network flow feature from different points of view and access the passenger MFD with three dimensions.

A robust controller was designed by Haddad and Shraiber [74] to deal with uncertainty in the MFD and aimed to satisfy the control specifications and achieve good performance for the whole accumulation set, uncongested and congested accumulations as well.

Many achievements in terms of MFD existence, shape, applicable conditions, influencing factors, and application direction have been achieved. Using the network dynamic MFD, real-time monitoring and adjustment of the vehicle aggregation state can be realized, thereby improving the urban maneuverability and alleviating traffic congestion. MFD is valuable when evaluating the implementing urban traffic network design and management-level control measures.

## 7. Solution Techniques to UTNDP

When it comes to resolutions to the transport design problem, there are two types of methods: accurate or mathematical method; heuristics algorithm or metaheuristics algorithm. Such exact methods as Branch and Bound Method (BBM) and branch-backtrack use mathematical programming techniques to solve the problem.

Heuristic algorithm essentially is based on experience or intuitive. It aims at providing a feasible solution at costs that can be accepted, especially time and space expensed in computation. Generally, deviation degree of the solution optimization cannot be predicted in advance. On the other hand, although the best solution is assured for heuristic algorithm, the feasibility and optimality are not guaranteed. Metaheuristic algorithm improved heuristic algorithm after integrating random algorithm into local search algorithm.

Metaheuristics covers Genetic Algorithm (GA), Simulated Annealing algorithm (SA), Ant Colony (AC), Scatter Search (SS), Tabu Search (TS), Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), and Ant System (AS) algorithm. There is no request for problem mathematical attributes and it is possible to obtain nearly global optimal solutions.

Some metaheuristics including GA, SA, Path Relinking, and Hill Climbing are used singularly or corporately for network topology design stage.

Results in [51] show that SA, GA, and TS have the similar performance. On the contrary, Hill Climbing alongside double neighborhood does not behave as well as that with single neighborhood. But if the application of GA and SA has inappropriate parameters, even if Hill Climbing alongside single neighborhood is somewhat simple, the algorithm efficiency is sometimes relatively high compared to the former two algorithms. What is more, in terms of the convergence speed, three algorithms, TS, GA, and Hill Climbing with single neighborhood, perform better and have higher speed of convergence than SA and Hill Climbing

with double neighborhood. It indicates that the solution number plays an obvious role in algorithms performance. Farahani and Miandoabchi et al. [4] summarized that the most popular algorithms applied in UTNDP are GA and SA. Some other researches have applied such algorithms as TS, SS, AC, AS, and POS. Apart from that, some researchers have attempted to combine metaheuristics, and results show that hybrid metaheuristics perform better than nonhybrid ones. In fact, the application of metaheuristics is normally related to MMNDP, TNDS, and DNDP, as these problems have discrete decision variables in these problems.

**7.1. Solution Algorithms to the RNDP.** The solutions for RNDP include exact methods, heuristics and metaheuristics. Mostly, DNDP applied branch and bound for the solution. In some research, RNDP is transformed into a single-level problem to use the branch and bound or other mathematical method. Gao and Wu et al. [75] transformed DNDP to a nonlinear programming problem. Gao and Sun et al. [13] developed a method for CNDP. MNDP is reformulated as CNDP by Haozhi and ZHANG [76], who solve the bilevel model through optimal-value function of the lower-level model in a gradient-based method. RNDP, in some research work, is directly formulated into a mathematical program with equilibrium constraints so that mathematical methods can be applied to solve the problem.

Secondly, heuristics, practically, are applicable for RNDP. This is obtained by transforming the bilevel model into a single-level model or a mathematical program with equilibrium constraints in advance. For example, Wang and Hong [17] transformed CNDP into a mixed-integer linear program and solved it using CPLEX.

Thirdly, many researches available in the literature of RNDP use metaheuristics or their hybrids to solve the problem. Few metaheuristics are applied in CNDP, while a large number of DNDP rely on metaheuristics. What is more, there are application of AS and its hybrids on DNDP with strategic decision. Applications of SA, GA, and TS can be found on DNDP with tactical decisions on the one-way streets orientation; PSO is used to determine the lane allocation. For tactical and strategic type of DNDP, a wide variety of metaheuristics are applied; furthermore, their hybrid is developed as well. Table 9 shows the summary of RNDP solutions.

**7.2. Solution Algorithms to the TNDP.** From strategic planning decisions level, TNDP consists of continuous and discrete optimization approaches. As for the latter, there are sequential approaches, metaheuristic algorithms, bilevel approaches, multiobjective TNDP approaches, and stochastic TNDP as well. Table 10 presents a summary of TNDP solutions.

**7.3. Solution Algorithms to the MMNDP.** As the MMNDP is highly complex and difficult to consider comprehensively, there are not so many literatures concentrating on this kind of problem; thus the solution techniques are few as well. Long and Gao et al. [19] developed a method that combined branch and bound algorithm with generalized reduced gradient

method. Most of the problems are solved with metaheuristics such as GA, SA, TS, and so on. SA, applied by Miandoabchi and Farahani et al. [21], has better optimization results than PSO, a harmony search and a clonal selection algorithm. With regard to some types of MMNDP, bus line frequencies or signal timings values, as the nontopological decision variables, are confirmed following metaheuristics generating optimal solution. In cases like that, lower-level problem is solved firstly; then variable values can be obtained to further calculate objective function optimal result.

## 8. Outlook

**8.1. Future Research for Directions of UTNDP.** Overall, great progress has been obtained in this area; examples are a wide range of mathematical models and solution methods have been applied to address traditional problems. Simultaneously, there are still many open topics causing more concerns and there are some gaps between literatures and real world, such as the following.

(1) Most studies of UTNDP have only one decision objective and most of objectives have focused on travel cost or travel time. Few researches take health cost or vehicle emissions into consideration. Environmental concerns should be concentrated on these problems due to the tradeoff between different objectives. Multiobjectives or optimization dimensions are more coordinated with the real world and whole system.

(2) The issue of multimodal is getting more and more concerns. Although existing researches on MMNDP are relatively limited, some studies are beginning to integrate road, bus, and metro together. Different modes flow interaction is significant as well. Also, under the background of share economy, nonmotorized traffic (NMT) became popular recently. More planning on NMT should be researched to comply with the requirements. The demand shares will vary as road network configurations change. Furthermore, the objective of MMNDP is to make use of resource efficiently, cut down on cost, ultimately, and improve the sustainability of society and transportation.

(3) New problems can be proposed by considering other transportation demands. With the rapid development of e-commerce in recent years and consumer demand patterns changing to be personalized and diversified, small-volume and high-frequency urban logistics distribution services have emerged, which means that the total amount of social traffic is increasing and freight vehicles frequently access to the central area of the city. Further, urban passenger traffic is affected and more congestion is generated. Urban logistics distribution is an important support for urban transportation system and economic development, and the issue of sustainable development of urban logistics should receive much attention. Urban logistics must not only form a social supply chain support capability for living activities, but also consider how to reduce the negative impact of logistics activities on cities.

(4) Compared with many considerations on urban main roads, the planning and construction of many urban branch



TABLE 9: RNDP solutions summary.

Reference	Objective	Demand	Decision	Traffic assignment	Solution method
Yang [6]	Max consumer surplus	E	Determining road tolls	DUE	Sensitivity Analysis Based method
Hai and Bell [7]	Max reserve capacity	F	Street capacity expansion	DUE	Nil
Meng, Yang et al. [8]	Min travel + construction cost	F	Street capacity expansion	DUE	Augmented Lagrangian Method
Meng and Yang [9]	Min total travel cost	F	Street capacity expansion	DUE	SA
[10]	Max reserve capacity	F	Street capacity expansion	DUE	SA
Gao and Song [11]	Max reserve capacity	F	Street capacity expansion; Scheduling traffic light	DUE	Sensitivity analysis based method
CHIOU and SuhWen [12]	Min travel + construction cost	F	Street capacity expansion	DUE	Four gradient-based methods
Gao, Sun et al. [13]	Min total travel cost	F	Street capacity expansion	DUE	Gradient-based method
Chiou [14]	Max reserve capacity	F	Scheduling traffic light	DUE	Hybrid Approach
Xu, Wei et al. [15]	Min travel + construction cost	F	Street capacity expansion	DUE	GA, SA
Mathew and Sharma [16]	Min total travel cost	F	Street capacity expansion	DUE	GA
Wang and Hong [17]	Min travel + construction cost	F	Street capacity expansion	DUE	Mixed integer linear program
Galloabb [18]	Min total travel time	F	Directions of existing roads; Signal settings at intersections	Asymmetric equilibrium assignment	SS based on a random descent
Long, Gao et al. [19]	Min total travel cost	F	Turning restrictions	SUE	BBM based on the sensitivity analysis algorithm
Miandoabchi and Farahani [20]	Max reserve capacity	F	Street directions; Lane additions	DUE	Hybrid GA and evolutionary SA
Miandoabchi, Farahani et al. [21]	Max consumer surplus Max demand share of the bus mode	F	Lane addition to the existing streets; New street constructions; Converting some two-way streets to one-way streets Lane allocation for two-way streets The allocation of some street lanes for exclusive bus lanes	DUE	Hybrid of GA and SA Hybrid of PSO and SA Hybrid of HS and SA
Miandoabchi, Daneshzand et al. [22]	Max reserve capacity; Min travel time	F	Optimal combination of one-way and two-way links; Street capacity expansion; Lane allocation	DUE	Hybrid GA; Evolutionary SA; Hybrid ABC

TABLE 9: Continued.

Reference	Objective	Demand	Decision	Traffic assignment	Solution method
Wang, Meng et al. [23]	Min total travel time	F	Adding new lanes	UE and SO	Mixed-integer linear programming
Long, Szeto et al. [24]	Min total travel cost; Min total vehicle emissions	F	Turning restrictions	SUE	Modified artificial bee colony (ABC)
Jiang and Szeto [25]	Max consumer surplus; Min health cost	F	Time-dependent network expansion		ABC
Liu and Wang [26]	Min total travel time; Min capacity expansion cost	F	Road capacity expansion	SUE	Mixed-integer linear programming
Szeto, Jiang et al. [27]	Max consumer surplus	F	Capacity expansion; Toll pricing; Cost recovery; Vehicle emissions	Lowry type equilibrium	ABC

road networks has been neglected. The scale and density of branch road networks are obviously lagging behind that of the main road systems. According to the urban transportation planning standard, the proportion of branch roads should be higher than that of the main roads in cities. However, it is the opposite indeed for most cities. The lack of branch roads contributes to congestion on the main roads and flows on main roads cannot be distributed easily. Less branch roads and microcirculation transit transportation cause inconvenience of transferring from other modes or traveling to some places. Here, microcirculation transit transportation means transportation service in local area, such as community. Microcirculation road network planning should include, but not limited to quality of life, customized traffic service, street safety, and influences on environment.

**8.2. Future Research for Mathematical Methods of UTNDP.** A wide range of mathematical models and solution methods have been applied to address traditional UTNDP. Other possibilities still remain for similar problem. And since problems types and complexity evolve, the mathematical methods need to evolve as well.

(1) Although GA has been proved to present better results than other algorithms in several studies, it is not clear whether other recently developed metaheuristics can outperform it. Examples of these new algorithms are firefly algorithm, differential evolution method, artificial immune systems, and cuckoo search. Therefore, future research could compare the performance of recently developed heuristics with the most commonly used algorithms now. Besides, each problem has its own properties, so it is essential to identify different problem properties and develop tailored algorithm for the problem. Tailored algorithm can be developed by combining different algorithms to make use of their strengths. For example, a hybrid of exact method and metaheuristics could

be developed to make a good trade-off between solution quality and speed.

(2) Some researches show that optimizing transport network by complex network theory is valuable. Complex network theory can be used to analyze transport network topology features, such as degree, clustering coefficient, and betweenness. These features help to recognize the problem of network and reflect its evolution rule. Network topology needs to be more concerned. For example, network topology has direct impacts on flow pattern and conflicts points at intersections. So the traffic signal setting will be affected as well. Apart from that, the vulnerability of urban transportation network under disruptions is still a big challenge for researchers. Jenelius and Mattsson [77] take Swedish road network modelling system as an example and find out the impact range of disruptions. Sullivan and Novak et al. [78] used independence of connectivity degree to assess network robustness when it has isolate link. Complex network theory is a favorable tool to find out the vulnerable nodes or edges and find a way to enhance the stability of the network.

## 9. Conclusions

We present, in this work, a literature review on cluster classifications, problems, mathematical models and their solution methods for UTNDP. The problems, models, and solutions are obtained according to CiteSpace cluster analysis. After reviewing the recently major UTNDP publications, we found that great progress has been obtained in this area. The classifications of problems and relevant models have been put forward and solved by different methods. The methods are listed and compared their strength. These researches provide helpful insights and inspire future possible directions such as topics on sustainability, multimodal network design, urban logistics, and branch road network design. Accordingly, solution methods should be evolved as well as discussed in Section 8.

TABLE 10: TNDP solutions summary.

Reference	Constraints	Objectives	Solution
Clarens and Hurdle [28]	Vehicle capacity	Min total users' and operators' costs	Analytical
CEDER [29]	Minimum frequency	Min excess travel time, transfer and waiting time	Heuristic
Chien and Schonfeld [30]	Vehicle capacity	Min total users' and operators' cost	Analytical
Chakroborty and Wivedi [31]	Route feasibility	Min unsatisfied demand, total travel time, and passengers with more than two transfers	GA
Wan and Hong [32]	Capacity and bounded frequency	Min operating costs	CPLEX
Guan, Yang et al. [33]	Demand satisfaction	Min in-vehicle travel time and number of transfer	Solver
Agrawal and Mathew [34]	Bounded frequency, load factor, and demand satisfaction	Min cost based on travel times and trip distances	Parallel GA
Anthony Chen and Yang [35]	Spatial equity and budget	Min total travel time	GA & Simulation
[36]	Headway bounds, load factor bounds, fleet size, trip length, and number of lines	Min weighted sum of user and operator costs	Decomposition & Heuristic
Gao, Sun et al. [37]	Minimum frequency	Min weighted sum of user and operator	Sensitivity analysis
CHIOU and SuhWen [12]	Link capacity	Min travel and construction costs	Gradient-based method
Fan and Machemehl [36]	Headway bounds, load factor bounds, line length, and fleet size	Min total users' and operators' costs	GA
J., Ch et al. [38]	Load factor and demand assignment	Min cost based on travel times, vehicle operations, and users' travel time	Heuristic
Mauttone and Urquhart [39]	Frequency bounds and load factor	Min users' cost vs. minimum fleet size	GRASP
Yang, Yu et al. [40]	Bus capacity, minimum direct travelers, and stop spacing	Max direct travels per unit length	ACO
Fan and Machemehl [41]	Headway bounds, load factor bounds, line length, and fleet size	Min total users' and operators' costs	TS
Guihaire and Hao [42]	Stopping time, running time, structure of each run, sequence of runs, the line daily bounds, time gap, interlining, the assignment	Min vehicle cost vs. Max service quality	Iterated local search algorithm
[43]	Vehicle capacity, number of lines	Min cost both for user and agency	
E, S et al. [44]	Bus capacity, feasibility constraints on route length and line frequency	Min all resources and costs	Heuristic route generation algorithm
Niu [45]	Timetable, cumulative passenger number, arrival and departure times, spillover queue, number of remaining passenger, capacity	Min waiting passengers number and weighted remaining passengers	GA, local improvement algorithm
Cancela, Mauttone et al. [46]	Transfer, street and bus capacity	Min the interest of the users and their behavior	MILP
Pternea, Kepaptsoglou et al. [47]	Resource availability, operating constraints, line structure constraints	Min passenger cost, operator cost, external cost	GA

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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