Practitioner Paper

A Parallel Transportation Management and Control System for Bus Rapid Transit Using the ACP Approach

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***Abstract*— Bus rapid transit (BRT) has been proved to be an effective tool to improve mass transit services. However, BRT's adaptive operations like management and scheduling under different scenarios are too complicated to implement using traditional methods. The ACP approach, which is based on holism and complex system theory and consists of artificial systems (A), computational experiments (C) and parallel execution (P), offers an efficient new method to cope with these complex systems, including BRT. In this paper, the parallel transportation management and control system for BRT (PTMS-BRT) is presented, which is designed and implemented using the ACP approach. PTMS-BRT integrates such functions as BRT's monitoring, warning, forecasting, incident management, and real-time scheduling, to provide its operations smoother, safer, more efficient, and reliable. It has been piloted successfully in Guangzhou BRT to demonstrate it as another successful example of parallel transportation systems.**

***Index Terms*— Bus rapid transit (BRT), ACP approach, parallel transportation system, dynamic perception, artificial transportation system.**

Manuscript received January 10, 2015; revised November 5, 2015, December 31, 2015, and September 26, 2016; accepted December 24, 2016. Date of publication January 31, 2017; date of current version August 28, 2017. This work was supported in part by the National Natural Science Foundation of China under Grant 61233001 and Grant 61304201, in part by the Guangdong Province S&T Department Project under Grant 2014A010103004, Grant 2015B010103001, and Grant 2014A050503004, and in part by the the National Science Foundation under Grant DUE-1140748. The Associate Editor for this paper was D. Work. *(Corresponding author: Gang Xiong.)*

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Digital Object Identifier 10.1109/TITS.2016.2645783

I. Introduction

Traffic congestion in urban areas has become a more serious issue worldwide due to the increasing of population, private and commercial vehicles, and the outdated infrastructure. Public mass transportation has been traditionally considered as the most cost-, energy-, and environmentally-efficient solution for urban traffic problems. However, the major types of public transit either require significant financial and time investment in construction and maintenance like subways and elevated trains, or lack of enough speed and capacity to provide fast and reliable transit service like normal buses.

Bus Rapid Transit (BRT) is a comprehensive urban mass transportation system that first debuted in Curitiba, Brazil in 1973 [1]. It is a bus-based mass transit system. Using primarily large-capacity low-floor buses, BRT integrates Intelligent Transportation Systems (ITS), bus-only lanes (BRT corridors), and rail traffic pattern operations management (pre-board fare collection) to offer a reliable, speedy, comfortable, and low-cost service [2], [3]. Combining the high capacity and speed of subways with the flexibility, economy, and simplicity of local bus systems, BRT offers an efficient and economical alternative to existing public mass transit systems [4]. Since its inception, BRT has been adopted by more than 150 cities in the world [1].

The key challenges of BRT are about its adaptive operations like management and scheduling, where the current implementations are struggling for. Due to its complicated nature, BRT cannot be clearly described using mathematical models, which makes its daily operations and scheduling difficult to apply traditional systematic management and control paradigms. The dominant BRT management and scheduling approaches in practice are combinations of simple control algorithms and trial-and-error methods. To fully harness BRT's efficiency and potential, new theories must be introduced to manage and control BRT's operations.

The ACP approach is a novel mechanism aimed at solving the modeling, analysis, management, and control of complex systems [5], [6]. Recently, the ACP approach has been successfully applied in the management and control of transportation systems [7]–[13]. In this paper, the ACP approach is used to design and build the Parallel Transportation Management and Control System for BRT (PTMS-BRT), which can provide

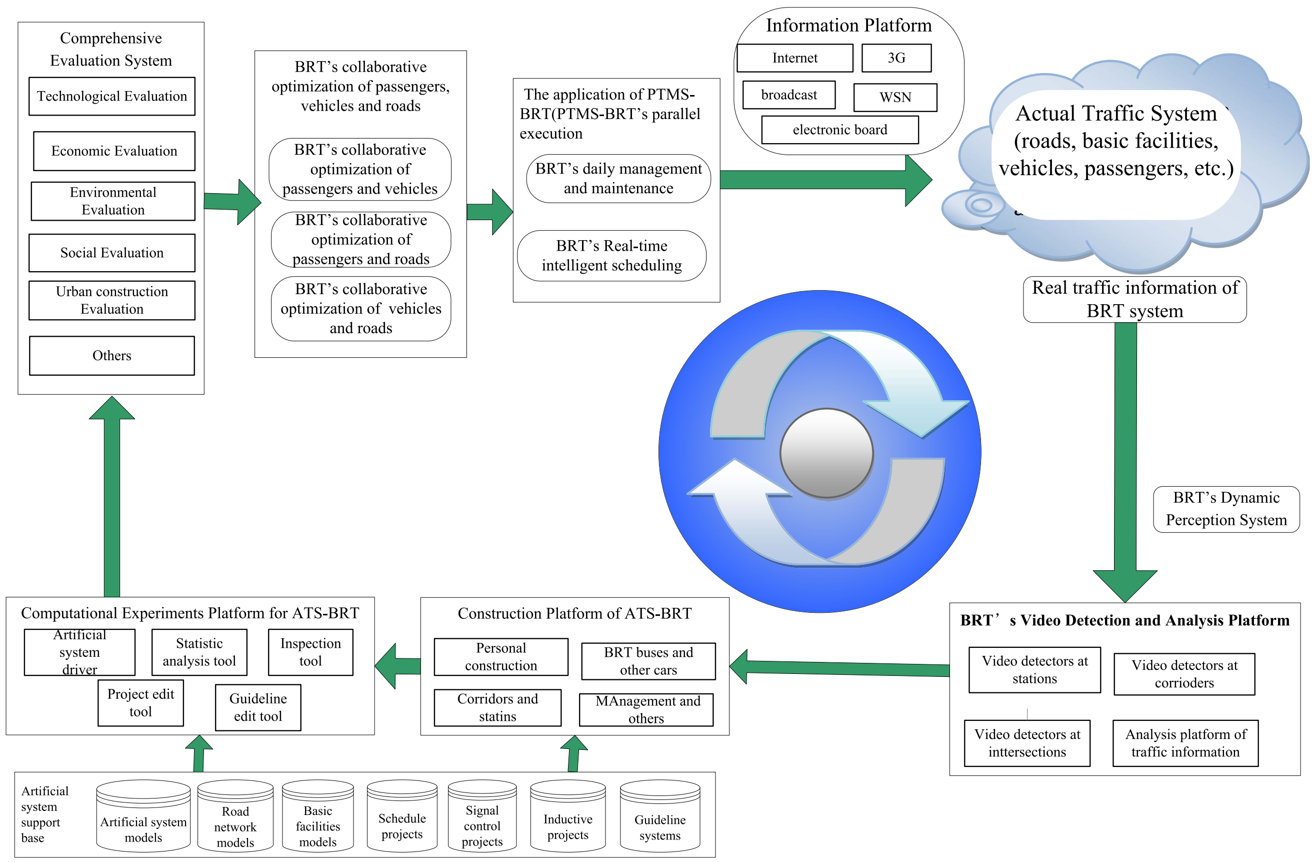

Fig. 1. PTMS-BRT architecture.

such functions as BRT's monitoring, warning, forecasting, incident management, real-time scheduling, and so on. A pilot project is done on the BRT system in Guangzhou, China, and shows its impact on making BRT operations smoother, safer, more efficient and reliable.

The rest of the paper is organized as follows: Section II introduces the architecture and functional subsystems of PTMS-BRT; Section III shows PTMS-BRT pilot applications in Guangzhou BRT; Section IV includes the conclusion.

II. Parallel Transportation Management and Control Systems for BRT

One successful ACP application in urban transportation systems is the design of the Parallel Transportation Management and Control System for BRT (PTMS-BRT). In this paper, we present a PTMS-BRT consisting of two sub-systems: *a*) Actual System (Dynamic Perception System of BRT); and *b*) Virtual System that includes Artificial BRT System (ATS-BRT), Comprehensive Evaluation System (CES-BRT), and Computational Experiments Platform (CEP-BRT). Figure 1 provides a graphical representation of overall system architecture. The system hierarchy is shown in Figure 2.

A. Dynamic Perception System of BRT

The Dynamic Perception System of BRT (DPS-BRT) carries out the following tasks to provide information feed of passenger flows, BRT vehicle locations, and road emergencies to allow administrative staff to track system safety, speed, reliability, and efficiency in real-time:

a) Data collection: GPS/GIS data, streaming videos from BRT vehicles, BRT stations, and intersections, etc.

b) Extraction and analysis of spatial and temporal distribution of BRT vehicles and passenger flows: BRT vehicle locations, queue length of BRT vehicles at stations and intersections, passenger density on BRT vehicles and at stations, etc.

c) Real-time transmission, monitoring, scheduling, information distribution, etc.

The information flow of DPS-BRT is presented in Figure 3, whereas Figure 4 shows DPS-BRT's screenshots running at Guangzhou BRT. This information can also assist road control systems in managing BRT vehicle priority at intersections.

B. Virtual Systems

1) Artificial BRT: ATS-BRT replicates the actual BRT in a virtual environment to provide an open and highly reliable test platform. Since BRT must take into consideration technical factors such as vehicles and roads as long as non-technical ones such as passengers, environment, and management, traditional methods including expertise modeling, mathematical modeling, and actual operational data modeling are inadequate to produce quality traffic models. Within the framework of the ACP approach, new modeling techniques are available to

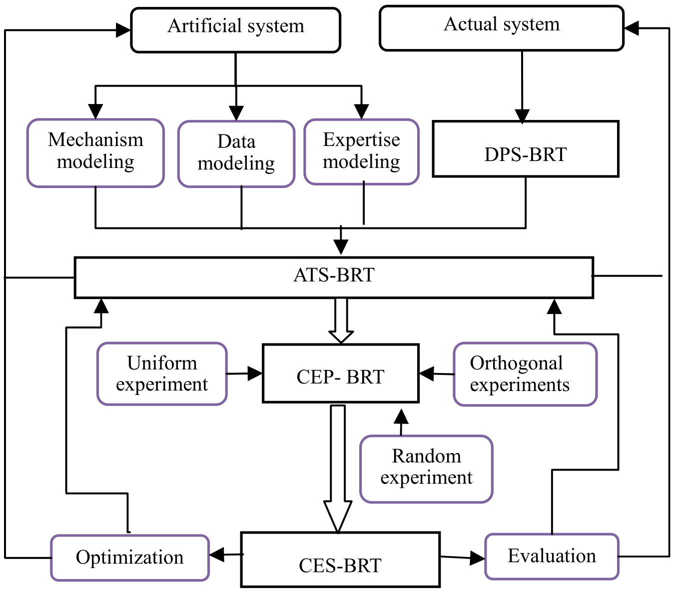

Fig. 2. Guangzhou PTMS-BRT Hierarchy.

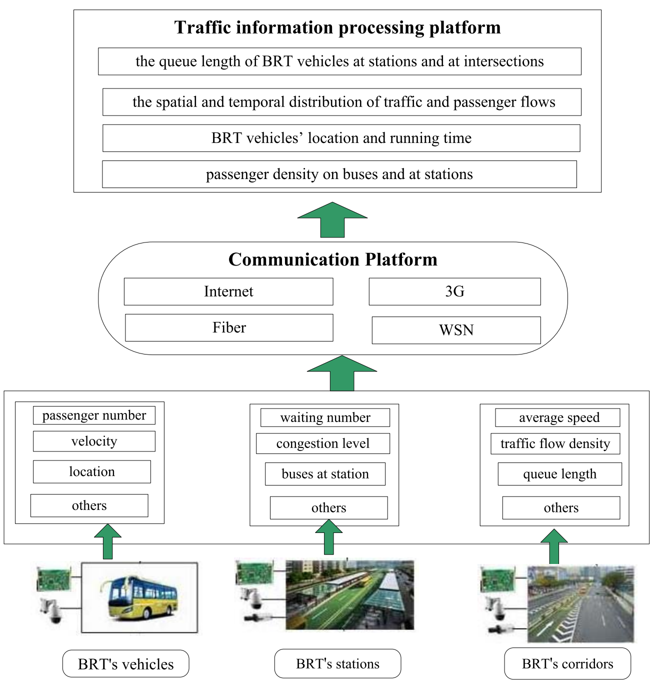

Fig. 3. DPS-BRT's Architecture.

ATS-BRT where mechanism modeling can be used to prototype "vehicles" and "roads"; agent modeling can be used to prototype "passengers", "environment" and other human and social factors; expertise modeling and data-driven modeling can also be deployed under proper scenarios.

The kernel of ATS-BRT is *TransWorld*, which is the basic design platform for Artificial Transportation System created by CASIA [7]–[12].

ATS-BRT consists of some functional modules: basic information, road network, transport vehicle, travel behavior, path planning, and micro-simulation traffic, etc. The basic information module stores and maintains those critical system's data:

TABLE I
BRT's Evaluation Index System

Evaluation Content	Evaluation index
Technological Evaluation	Departure frequency
	Capacity
	Velocity
Economic Evaluation	New technology development
	Travel time saving
	Employment number
Environmental Evaluation	Greenhouse gases emissions
	Pollutants emissions
	Noise level
Social Evaluation	The proportion of ticket cost
	The proportion of travel mode
	Passenger satisfaction
Urban construction Evaluation	Transit-oriented development
	Business activities
	Real estate development
Others	Large-scale activities
	Incident management and plans
	The collaboration of people, vehicles, and roads

a) BRT stations information: names, locations, station numbers, lengths, uplinks/downlinks, etc.
b) BRT channels (connecting adjacent stations) information: names, locations, lengths, uplinks/downlinks, etc.
c) BRT intersections information: names, location intersection numbers, traffic control status, etc.
d) BRT lines information: names, stopping stations, fleet size, etc.
e) BRT vehicles information: license numbers, GPS codes, routes, uplinks/downlinks, vehicle modes (shuttle, express, etc.), locations, velocities, etc.
f) BRT management center: rules and regulations, scheduling strategies, timetable, etc.
g) Related personnel information: passengers, drivers, crew members, managers, etc.
h) Environment information: environment, weather, transportation facilities, etc.
i) Other information: company benefits, social benefits, passenger satisfaction, vehicle scheduling, personnel scheduling, etc.
j) Database: storing historical data, operations rules, expert experience, etc.

With joint execution of all modules, ATS-BRT helps gain the insight about the evolving relationship and interactions between different elements of the traffic systems.

Figure 5 shows the ATS-BRT user interface for Guangzhou BRT. As the world's second largest BRT in terms of passenger flows, it controls 26 stations and 44 bus lines.

2) Comprehensive Evaluation System for BRT (CES-BRT): The multi-level and multi-objective CES-BRT is constructed using Fuzzy Analytic Hierarchy Process (FAHP) [14]. The goal is to offer a wide-ranging evaluation of ATS-BRT from technology, economy, environment, social and urban development, traffic regulations, and incident management, to the coordination of passengers, BRT vehicles, roads, stations, and

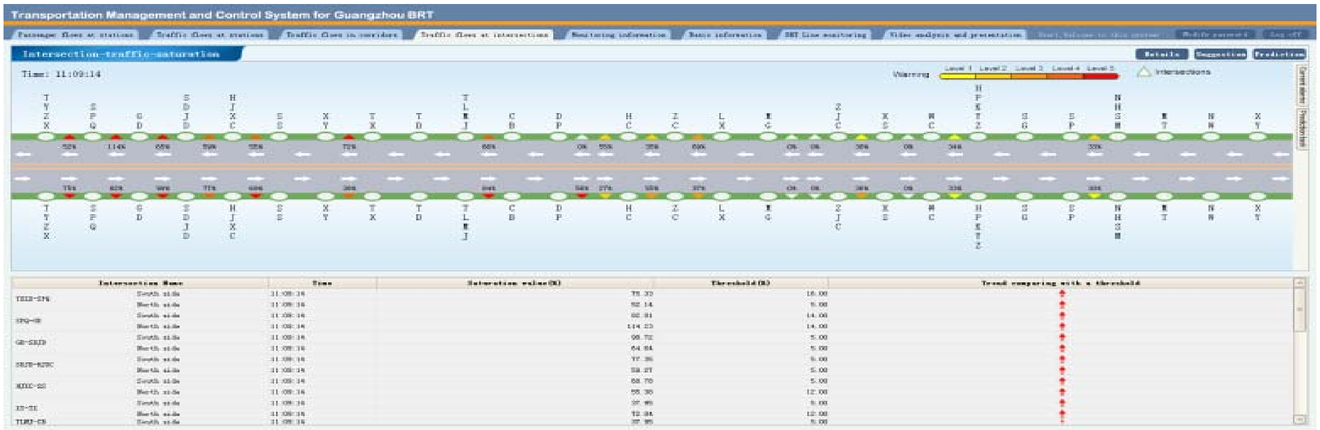

Fig. 4. BRT's Dynamic Perception System.

Fig. 5. ATS-BRT Interface for Guangzhou BRT.

Fig. 6. Computational Experiment and Results Analysis on CEP-BRT.

policies (See Table I). CES-BRT is capable of evaluating both the actual BRT operations data and ATS-BRT data.

3) Computational Experiments Platform for ATS-BRT (CEP-BRT): Computational experiments aim to simulate key indices such as transit service levels, bus scheduling plans, passenger waiting times, economic constraints, environmental impact, resource consumption, and management plans for emergencies and major events. CEP-BRT is a scenario generator that can create real and virtual experiment scenes simultaneously. It accepts scenario input directly from end-users or scenario library.

After instantiating the related scenario interaction mechanism and control rules, the data is forwarded to the event-driven simulation engines, which are the core of CEP-BRT. Based on discrete event simulation technology, the engines can run experiments at the designated times using simulation clock platform, or be triggered by the specified discrete events. The experiment results are saved chronologically to facilitate the analysis of the relation between triggering and triggered events.

To help dynamically analyze and evaluate experiment results, CEP-BRT incorporates numerous computing algorithm analysis tools such as group strategy learning and optimization algorithm, qualitative and quantitative assessment algorithm, and other specific algorithm modules for various applications.

By using different scenarios and experiment construction schemes such as uniform experiments, orthogonal experiments, and random experiments, CEP-BRT can test and verify the various traffic patterns in a cost-effective and risk-free fashion to generate comprehensive, accurate, and real-time assessment, and the different traffic management strategies. In conjunction with CES-BRT, CEP-BRT's results will obtain the collaborative optimization under ATS-BRT for various Key Performance Indicators (KPIs).

Figure 6 illustrates CEP-BRT forecasts for the impact that different scenarios have on BRT traffic flows. The two KPI's considered in this experiment are the average number of overflown BRT corridors and overflown intersections, represented by the orange bar (the left part of every bar) and green bar (the right part of every bar), respectively. The scenarios are generated by imposing a 5%, 10%, 15%, 20%, and 25% adjustment on actual data. The results reflect the projected traffic pattern changes under different adjustments of actual data; for instance, the first set of bars indicates that under the 5% adjustment, there are 29 BRT corridors and

Fig. 7. Statistical report.

25 intersections which will exceed the pre-defined thresholds of traffic saturations in 20 minutes.

III. PTMS-BRT Application

PTMS-BRT has been piloted successfully in Guangzhou BRT, Guangzhou China, which has the world's second largest passenger flow, to improve its adaptive management and control and to help Guangzhou win the Sustainable Transportation Award of The United States Transportation Research Board (TRB). There are 44 routes, including short & express route variations, all or partly operating inside BRT corridors. And there are >75% of stations including two or more substations. The length of the longest BRT station is 285 meter. So, Guangzhou BRT carries about 850,000 passengers per day, are the only two BRT systems (anther one is Transmilenio of Bogotá, the capital of Colombia) worldwide that can carry more than 25,000 passengers per hour in a single direction past a single point, which is higher than the most metros (subways) and all light rail lines worldwide.

A. Daily Management and Maintenance

It can execute Guangzhou BRT's daily management and maintenance, including the following functions:

a) Managing administrative staff, drivers, vehicles, maintenance, scheduling, etc.
b) Real-time monitoring BRT routes and control centers; passenger flows at stations; traffic flows at stations, at intersections, and in corridors.
c) Reporting road-side incidents, over speed, vehicle mechanical failures, etc.
d) Recording BRT vehicle GPS information, vehicle arrival/departure times, etc.
e) Generating BRT statistics reports for passenger throughputs, vehicle occupancies, fares, complains, trips, fuel consumption, mileage, etc.

Figure 7 shows the interface of Guangzhou PTMS-BRT system. The real-time information shown in the screenshot includes the locations, distribution, running status, and dispatching of all BRT vehicles in service.

Detail service information about the BRT vehicles is updated in real-time and can be monitored by the BRT operators through the graphical user interface. The information includes drivers' names and vehicles' license numbers, routes, origins, stopping stations, running status, start times, and service times.

B. Collaborative Optimization of Passenger Flow, BRT Vehicle Dispatch, and BRT Routes

To achieve collaborative optimization, the system utilizes the synergistic evolving rules incorporated in the CES-BRT. With CES-BRT functioning as the standard evaluation system, computational experiments assess various BRT benchmarks such as service levels, accident rate, wait times, economic constraints, environment impact, resource consumptions, regulatory effect, traffic rules and regulations, routes and scheduling optimization, etc.

1) Optimization of BRT Routes and Stations: The goal of this optimization is to produce an even or balanced passenger distribution. CES-BRT uses CEP-BRT to conduct rolling optimization through historical and real-time videos, including 1) alter the substations of one route stopping a station to make the number of passengers of different substations more even or uniform, 2) alter the route modes (regular, short & express), 3) alter (alter/add/reduce) the routes all or partly running inside BRT corridors.

2) Collaborative Optimization of Passenger Flow and Vehicle Dispatch: This optimization focuses on controlling the overall BRT traffic based on passenger flow forecasts and the real-time data to ensure collaborative saturation optimization between the number of BRT vehicles and the passenger throughput. The objective is balancing the effectiveness (minimizing passenger waiting and traveling time) with the efficiency (maximizing the number of passengers per vehicle and BRT profit).

Passenger flow forecasts rely on available flow data along with OD data prediction, historical reference, objective information, and logical decisions. By analyzing the influence of city planning, population growth, and economic activities on passenger throughputs, forecast models can estimate the changing passenger patterns and trends. For Zhongshan Highway BRT, real-time data is collected from BRT's operations scheduling management system and the traffic card information is collected from *Yangchengtong* (http://www.gzyct.com); along with video-based detection systems on BRT vehicles, at BRT stations, and at the controlled intersections. Forecasting results of passenger flows can be verified and then adjusted using real-time data.

3) Collaborative Optimization of BRT Vehicles and Roads: This optimization involves reducing BRT vehicle's waiting times at the controlled intersections while minimizing the increase of wait times for other vehicles and pedestrians. Absolute controlled intersection priority allows BRT vehicles to enter intersections without delays, however heavy cross traffic can easily lead to gridlock after the BRT vehicle leaves. Consequently, relative priority strategy is widely used these days. Contrary to absolute priority where current signal phases are interrupted unconditionally, relative priority allows the timing of different phases in a signal cycle to be adjusted to give BRT vehicles shorter waiting times.

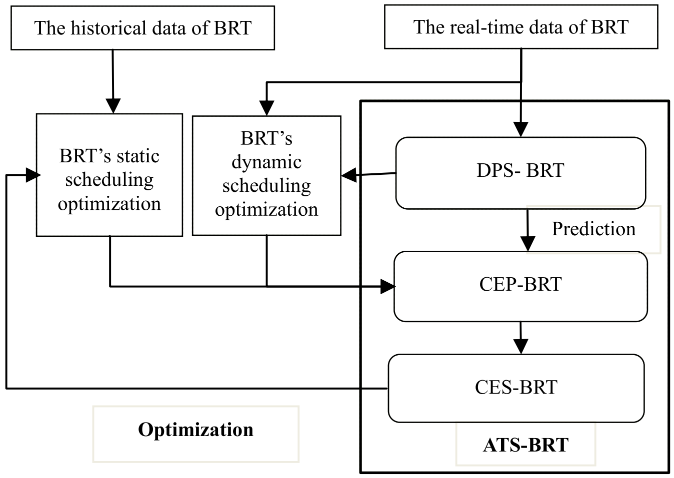

Fig. 8. Scheduling optimization.

C. Real-Time Intelligent Scheduling Based on PTMS-BRT

Figure 8 illustrates various components of PTMS-BRT working cohesively to achieve intelligent scheduling: ATS-BRT forecasts system loads; real-time information from DPS-BRT is used to adjust BRT vehicles' Transit Signal Priority (TSP) control at intersections and calibrate ATS-BRT; CEP-BRT computes and analyzes various operations plans originally made by experts manually; CES-BRT compares and evaluates these plans based on standards (KPI) such as the static scheduling stage before BRT's operations (driving plan, time schedule, vehicles arrangement, etc.), the dynamic scheduling stage during BRT's operations, and the analysis stage after BRT's operations (reports, statistics, index analysis, etc.) [15], [16].

We proposed and implemented a simple, flexible, and practical real-time scheduling method that only requires passenger density at BRT stations [15]. Comparing the departure frequency of Line B1 in Guangzhou BRT before and after the deployment of the aforementioned PTMS-BRT, the total departures were decreased from 144 vehicles/day to 133 vehicles/day, meanwhile, the morning and evening peak's vehicle density were increased and passengers' average waiting times were reduced.

IV. Conclusions

In this paper, the ACP approach is adopted to design and build up PTMS-BRT for BRT's adaptive operations. It can use real-time traffic information, advanced modeling and simulation tools, and comprehensive evaluation mechanism to forecast BRT's passenger and traffic flows, and can achieve collaborative optimization of the passenger flows and the corresponding vehicle dispatches. PTMS-BRT has been piloted successfully in Guangzhou BRT, to improve its smoothness, safety, efficiency, and reliability by strengthening such functions as its daily management, monitoring, warning, forecasting, incident management, and real-time scheduling.

Acknowledgment

The authors would like to thank Prof. F.-Y. Wang for his guidance and help in the design and implementation of this project. They would also like to thank Dr. Steve Nobe for reviewing the manuscript and offering valuable feedback.

References

[1] L. A. Lindau, D. Hidalgo, and D. Facchini, "Bus rapid transit in Curitiba, Brazil a look at the outcome after 35 years of bus-oriented development," *Transp. Res. Rec.*, vol. 2193, pp. 17–27, Dec. 2010.

[2] R. Cervero, "Bus rapid transit (BRT): An efficient and competitive mode of public transport," Inst. Urban Regional Develop. (IURD), Working Paper 2013-01, Aug. 2013, pp. 1–45. [Online]. Available: http://escholarship.org/uc/item/4sn2f5wc

[3] L. Wright and W. Hook, "Bus rapid transit (BRT) planning guide," Inst. Transp. Develop. Policy, New York, NY, USA, Tech. Rep., Jun. 2007. [Online]. Available: https://www.itdp.org/wp-content/uploads/2014/07/Bus-Rapid-Transit-Guide-Complete-Guide.pdf

[4] J. Hecker, "Bus rapid transit offers communities a flexible mass transit option," in *Report for the Committee on Banking, Housing, and Urban Affairs, US Senate*. Washington, DC, USA: General Accounting Office, 2003.

[5] F. Y. Wang, "Artificial societies, computational experiments, and parallel execution: An investigation on computational theory of complex social-economic systems," *Complex Syst. Complex. Sci.*, vol. 1, no. 4, pp. 25–35, 2004.

[6] F.-Y. Wang, "Toward a paradigm shift in social computing: The ACP approach," *IEEE Intell. Syst.*, vol. 22, no. 5, pp. 65–67, Sep. 2007.

[7] F.-Y. Wang, "Parallel control and management for intelligent transportation systems: Concepts, architectures, and applications," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 630–638, Sep. 2010.

[8] S. H. Chen, F. H. Zhu, and J. P. Cao, "Growing spatially embedded social networks for activity-travel analysis based on artificial transportation systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 5, pp. 2111–2120, Oct. 2014.

[9] Q.-J. Kong, L. Li, B. Yan, S. Lin, F. Zhu, and G. Xiong, "Developing parallel control and management for urban traffic systems," *IEEE Intell. Syst.*, vol. 28, no. 3, pp. 66–69, May/Jun. 2013.

[10] F. Zhu, D. Wen, and S. Chen, "Computational traffic experiments based on artificial transportation systems: An application of ACP approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 1, pp. 189–198, Mar. 2013.

[11] G. Xiong *et al.*, "Parallel traffic management system helps 16th Asian games," *IEEE Intell. Syst.*, vol. 27, no. 3, pp. 74–78, May 2012.

[12] G. Xiong, X. Dong, D. Fan, F. Zhu, K. Wang, and Y. Lv, "Parallel traffic management system and its application to the 2010 Asian games," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 1, pp. 225–235, Mar. 2013.

[13] B. Ning, H. R. Dong, D. Wen, L. F. Li, and C. J. Cheng, "ACP-based control and management of urban rail transportation systems," *IEEE Intell. Syst.*, vol. 26, no. 2, pp. 84–88, Mar./Apr. 2011.

[14] Z. Xu and H. Liao, "Intuitionistic fuzzy analytic hierarchy process," *IEEE Trans. Fuzzy Syst.*, vol. 22, no. 4, pp. 749–761, Aug. 2014.

[15] G. Xiong *et al.*, "Continuous travel time prediction for transit signal priority based on a deep network," in *Proc. 18th Int. IEEE Conf. Intell. Transp. Syst.* Sep. 2015, pp. 523–528.

[16] X. S. Dong, G. Xiong, D. Fan, F. H. Zhu, and Y. S. Lv, "Research on bus rapid transit (BRT) and its real-time scheduling," in *Proc. IEEE Int. Conf. Service Oper., Logistics Informat.*, Beijing, China, Jul. 2011, pp. 342–346.