Parallel Transportation Management and Control System and Its Applications in Building Smart Cities

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***Abstract*—Advancements in complexity, complex systems, and the intelligence sciences, particularly smart city technologies, have shown great potential in aiding to ease traffic congestion. The overall approach and the main ideas in building smart transportation for smart cities, particularly ACP (artificial system, computational experiment, and parallel execution)-based parallel transportation management and control systems (PTMS), are presented. PTMS can be expanded to the new generation of intelligent transportation systems. The main components of the proposed architecture include social signal and social traffic, ITS clouds and services, agent-based traffic control, and transportation knowledge automation. Some technical details of these components are discussed. Finally, one case study is introduced, and the effectiveness is analyzed.**

***Index Terms*—Intelligent transportation systems (ITS), artificial system, computational experiment and parallel execution (ACP) approach, parallel transportation management and control system (PTMS), computational experiment, ITS cloud, social transportation, transportation knowledge automation.**

I. INTRODUCTION

WITH the constant progress of global urbanization, complex economy situation, increasingly severe shortage and emergence of social contradictions, etc., urban development is brought with huge challenge. Smart city construction is the inevitable choice for realizing the strategic target for constructing a livable and modernized international city.

Although there is not yet a formal definition of "Smart City," it is widely accepted that the final aim is to make a better use of the public resources, increasing the quality of the services that offered to the citizens, while reducing the operational costs of the public administrations [1]. According to World Bank's estimates, in the case of investment unchanged, the development dividend can be increased by 2.5 to 3 times through the construction of smart city for a city with more than one million people. According to one estimation, the specific effects of smart cities include: 10-fold return on the whole society, manufacturing productivity increased by 5%, the service sector productivity increased by 10%, GDP growth in the contribution rate of 0.71%, an increase of 107 000 jobs each year, 1.7-fold pulling on the downstream and upstream industries comparing to traditional industries.

Smart transportation is playing an important role for the implementation of smart city. On one hand, more intensive effort is needed to be put into traffic control and management research as the urban congestion problem is becoming an increasingly major issue, both in developed countries and emerging new powers. For example, the rate of urbanization in China is over 52% and is expected to grow more than one percent every year, and achieve a relatively stable level about 70% in 2030. This rapid increase in metropolitan population and other urbanization activities have imposed a huge demand on Chinese metropolitan transportation systems, most of which weren't prepared for such development [2]. On the other hand, recent R&D advancements in complexity, complex systems, and the intelligence sciences, especially smart city technologies, have shown great potentials in aiding to ease traffic congestion. For example, on Beijing's ring roads—concentric circles around the city—157 high-definition cameras automatically count vehicles and provide traffic flow statistics. When events such as accidents, congestion, and surface water accumulation occur, the system automatically videotapes the event and activates an alarm as needed. Tens of thousands of detecting coils embedded in expressways and trunk roads near intersections automatically collect traffic flow, speed, and density data through electronic induction. Ultra-sound, microwave, video, and other technologies provide traffic information for integration, analysis, and processing [3]. In Nanjing, 1,800 buses are equipped with 4G network transmitters that interact with 52 base stations along the bus lines, allowing passengers free Internet access to information such as the time of the next bus [4].

To some extent, current ITS can be regarded as being established based on cyber physical system (CPS), which have been studied extensively. Derler *et al.* [5] focused on the challenges of modeling CPSs that arise from their intrinsic heterogeneity, concurrency, and sensitivity to time. CPS should consider the close interactions between the physical system and its cyber system both in time and space dimension. These interactions are usually governed by events, which occur in physical system and should autonomously be reflected in its cyber system. By exploring the temporal and spatial properties of events, Tan *et al.* [6] developed a layered spatio-temporal event model for CPS, where the event is represented as a function of

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attribute-based, temporal, and spatial event conditions. Over the years, various techniques, algorithms, specification logic and software tools have been developed for simplifying CPS models to achieve certain verification goals [7], [8].

Technological changes and theoretical developments have created opportunities for fundamental restructuring of transportation management that could lead to significantly expanded capacity and improved efficiency. Recently, an opinion is proposed that we must add and address the human and social dimension present in CPS. This is largely due to the unprecedented sphere and speed of influence experienced in the cyberspace field and its profound impact on the way we behave and interact with each other. This tendency is also clear in transportation research [9]. Chinese AI researchers have been working on ways to transform systems and methods along this direction. This paper centers on the ACP (artificial system, computational experiment and parallel execution) approach. This approach involves modeling with artificial systems, analysis with computational experiments, and operation through parallel execution for control and management of complex systems with social and behavioral dimensions [10], [11].

To utilize latest advanced technologies, especially Internet of Things (IoT) and cloud computing, and speed up the R&D effort in traffic control and management, particularly at the system level, we need new thinking and a multidisciplinary approach. In this paper, we present the overall approach and the main ideas in building smart transportation for smart cities, particularly ACP-based parallel transportation management and control system (PTMS). The contributions of this paper mainly include:

1) A novel architecture for building new generation ITS based on PTMS is proposed and some components of the architecture are analyzed in details.
2) The general process of generation and dissemination of social signal in social transportation is discussed and crowdsouring platform for transportation is established accordingly.
3) Traffic computational experiments based on PTMS are carried out and numerical results are analyzed to verify the effectiveness of the architecture.

The remaining sections of this paper are organized as follows: Section II introduces the main ideas of PTMS and the architecture of the new generation of ITS based on PTMS. Sections III and IV discuss two basic components in the architecture, namely, social signal & social traffic and ITS clouds & services, respectively. Section V introduces one case study. Section VI summarizes this paper.

II. Parallel Transportation Management and Control Systems (PTMS)

A. ACP Approach and PTMS

Urban transportation systems are typical complex systems, and how to utilize the research results from studying complex system and intelligence science to address the problems in the management and control of transportation systems, such as new methods for the modeling, experiment, optimization and evaluation problems, has become one hot topic. Among them, ITS based on ACP approach, which promotes traditional traffic simulation to higher lever and wider perspective, has grown maturity gradually both in research and applications and has been interested by the researchers throughout the world [15]–[18]. The ACP approach can be described as the follows 3 steps [12]: first, considering engineering, social, human and environmental factors together as a whole, synthesizing theoretical models, empirical models and data models, establishing the equivalent Artificial system for the actual system to address the model problem for complex systems (A); second, studying the interactions and evolution rules of the elements in the actual system by carrying out Computational experiments on the artificial system under both normal and abnormal conditions (C); third, connecting the artificial system and the actual system, carrying out Parallel execution by comparing and analyzing the behaviors of the two types of systems, referring and forecasting the future conditions, and adjusting the control and management methods of the two systems accordingly (P).

Based on ACP approach, a new concept, parallel transportation management and control system, is proposed by Prof. Wang to resolve the optimization and evaluation problems in transportation systems [12]. By connecting the actual transportation system and the artificial transportation systems, experiments can be carried on the artificial transportation and the optimization and evaluation can be implemented conveniently. The artificial transportation systems provide the hardware-in-the-loop mechanism and general external interfaces, which enable the interactions between the actual devices and the artificial software modules. When the experiment is running in hardware-in-the-loop mode, the actual devices, such as signal controller and vehicle detector, can be embedded into the artificial transportation systems. In this mode, the actual detectors can access the traffic flow parameters in the artificial road network, and the actual controllers can send commands into the artificial transportation systems and influence its running status by changing the artificial traffic lights, and vice versa. Besides generating MOEs for quantitative analysis, the execution process can also be replayed using 3D animation, which can show the movement process of vehicles in details both in space and time dimension [14].

B. Why is ACP for Transportation Systems

The ACP approach was originally proposed in [19]–[21] for the purpose of modeling, analysis, and control of complex systems, which have the following two essential characteristics:

- *Inseparability*. Intrinsically, with limited resources, the global behaviors of a complex system cannot be determined or explained by independent analysis of its component parts. Instead, the system as a whole determines how its parts behave.
- *Unpredictability*. Intrinsically, with limited resources, the global behaviors of a complex system cannot be determined or explained in advance at a large scope.

The main feature of our method is that the optimization and evaluation are all based on the interactions between the actual transportation system and the artificial transportation systems.

On one hand, comparing to using traditional simulation software or mathematics models, more factors can be modeled, thus reasonable scenarios can be generated, and higher reliability can be achieved. On the other hand, comparing to carrying out experiments using actual devices in field, the environment can be controlled and it is possible to carry out the experiments under abnormal conditions. Accordingly, the experimental cost can be reduced to a very low level and abundant results can be obtained easily. As a result, the feasibility and reliability of the experiments are improved.

As mentioned before, in order to obtain reliable result, computational experiments in various scenarios should be carried out. Besides traffic subsystem, the scenarios will also cover social and economic aspects, as transportation is connected with the environment tightly. From micro activities, such as individuals' psychology and driving behavior, to macro phenomena, such as travel gross and travel distribution, all are influenced by the environment. The mechanisms by which the environment influences traffic status are very complex and there are still many disputes about how to model the influences using a top-down reductionism method. However, for simple objects, such as individual vehicle and local traffic behavior, most of current conclusions about the influences that they receive from the environment are consentaneous. So if we set up models for simple micro objects and local behavior using these widely approved conclusions, the macro complex phenomena that emerged from these simple objects are also expected to be understandable and agreeable. This idea for modeling transportation system can be abstracted as simple-is-consistent and has been widely used in designing computational experiments based on ATS. It has been proved that, using this idea, ATS not only can model direct traffic-related activities, but also can generate difference traffic processes under various indirect facilities and activities conditions. Thus, it provide us a natural way to study the influence of weather, legal, social and other involvements.

C. The New Generation of ITS Based on PTMS

In this background, a new generation of ITS, Transportation 5.0, is proposed by Prof. Wang in 2014 [21]. It is our belief that, though we are still in the early stage of CPS-based Transportation, it is time to promote the field of Computational Transportation as a research direction to integrate and lift the current work in computer simulation and computational analysis of transportation systems to a new generation, where powerful new computing methods, advanced sensing techniques, and big data in cyber, physical, and social spaces can be easily utilized—much like what has happened in computational mechanics, computational fluid dynamics, computational physics, computational chemistry, computational social studies, and many other computational X [21].

The architecture of the new generation of ITS, which is a natural expansion and generalization of PTMS, is shown in Fig. 1. Besides utilizing IoT and cloud computing technologies as the foundation, two characteristics are social transportation and agent-based systems. On one hand, Transportation is a direct result of human and social activities, thus, social and human dynamics must be considered an integral part of any effective transportation system design and operation and we must have social component explicitly represented in transportation research and development. On the other hand, the step from control algorithms to control agents is a natural development of control engineering in the age of connectivity and control will become an independent entity instead of an affiliated function in system design. Thus, the development of a theoretical framework for agent-based control systems will significantly advance knowledge of control engineering in this new age [22].

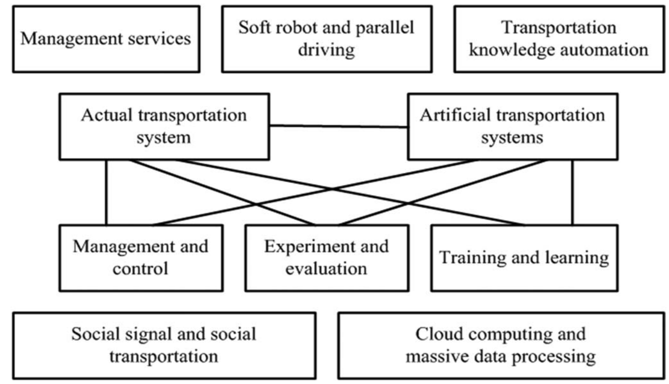


Fig. 1. The architecture of transportation system based on PTMS.

Agent-based traffic management systems can use the autonomy, mobility, and adaptability of mobile agents to deal with dynamic traffic environments. With mobile agent technology, an urban-traffic management system based on Agent-Based Distributed and Adaptive Platforms for Transportation Systems (Adapts) is both feasible and effective. However, the large-scale use of mobile agents will lead to the emergence of a complex, powerful organization layer that requires enormous computing and power resources. To deal with this problem, we propose a prototype urban-traffic management system using intelligent traffic clouds. Cloud computing can help such systems cope with large amounts of storage and computing resources required to use traffic strategy agents and mass transport data effectively. Intelligent transportation clouds could also provide services such as decision support, a standard development environment for traffic management strategies, and so on.

In the new generation of ITS, we need new thinking and a multidisciplinary approach to coordinate our research and systematic effort with those emerging methods and techniques. In this way, transportation knowledge automation based on Web data mining can play an important role. Knowledge automation is not to generate knowledge automatically, but it can facilitate the innovations in all aspects of knowledge, such as broadcasting, acquiring, analyzing, influencing, and generating. MOOCs provide us one living example and knowledge automation is sure to play an important role in its future development.

III. Social Transportation

A. Social Signal and Social Transportation

With the advance of Internet and Web technologies, the increasing accessibility of computing resources and mobile devices, the prevalence of rich media contents, and the ensuing social, economic, and cultural changes, computing technology and applications have evolved quickly over the past decade. They now go beyond personal computing, facilitating collaboration and social interactions in general. As such, social computing, a new paradigm of computing and technology development, has become a central theme across a number of information and communication technology (ICT) fields [23], [24].

Transportation develops with the society, and there is obviously a bidirectional interrelationship between the two. This has attracted many researchers' attentions. In the 1990s, sociology researchers proposed the discipline architecture of "The Sociology of Transportation," and addressed that transportation is the result of the development of society, and people's contacting is the essence and reason of transportation [25]. Meanwhile, researchers on Intelligent Transportation Systems (ITS) study transportation problems mainly from the perspective of engineering, such as traffic signal, route guidance, and driving safety. However, as people concern the safety, low carbon, environmental protection, and human-centered increasingly, transportation related studies must consider more factors, such as society and people. Therefore, social transportation systems are becoming an essential component in establishing transportation systems. As like as many existing crowdsourcing platforms (e.g., Quora, Stack Overflow, Baidu Wenda), a mechanism to detect wrong or false information released by malicious or careless users is quite important for the proposed platform. First, there is a pressing need to make proper laws to restrict people's online actions, like real-name authentication and rumor prohibition. Second, several effective technologies have been explored to reduce risk of misleading. Two of them are listed here as examples : 1) allow users to score others' information, then the information with high score probably should have high reliability; 2) apply recommendation technology to select reliable information or people to answer the questions. Last but not least, the information generated on social media can only be used as a reference, and its quality should be further judged by the real person that are interested in it.

The sociology of transportation focuses on the relationships among transportation and various social factors mainly from the perspective and method of sociology, and aims to find out useful laws for future development. By contrast, social transportation systems emphasize real-time computing and embedded applications in transportation systems with online social signal. Since social signal is all-embracing and involves human factors, the collecting and processing procedures are relative more difficult. However, as the (mobile) Internet has come to increasingly prevalent in every aspect of our lives, the emerging technologies like cloud computing and Internet of Things (IoT) are used more and more widely, and intelligent mobile devices like smart phone and wearable devices are becoming more and more popular, it is now possible for machines to capture and manipulate huge social signal automatically. Real-time and reliable social signal will be essential for society management, especially for new close-loop society emergency management [26].

Generally speaking, the generation and dissemination of social signal can be divided into four stages: 1) thought generation, 2) broadcast channel, 3) interpretation process, and 4) social sentiment, as shown in Fig. 2. After thought is generated by some persons, it may be released through varied channels first, and then disseminated through traditional media or new social media like forum, blog and micro-blog. The disseminated social signal will be received and interpreted by people and organizations, and then fused with their physical and mental states, and transferred into sorts of social sentiment finally.

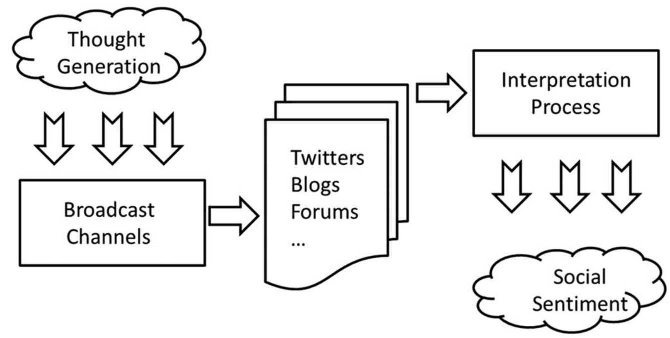


Fig. 2. The general process of generation and dissemination of social signal.

In physical space, varieties of sensors as well as their sensing networks are the main medias to acquire physical signal. In a similar way, collecting social signal needs social sensor and social sensing networks. Fortunately, existing websites, blog, forum, micro-blog and various apps can be used as social sensors naturally, and the (mobile) Internet can be treated as the social sensing network correspondingly. What people actually need to do is mining and finding out useful information from huge amounts of data. However, it should be noted that physical sensor systems is still indispensable, since plenty of social information can be mined from physical signal like camera, GPS, smart cards and so on.

B. Crowdsourcing Platform for Transportation

Currently, social transportation systems are under-going trials, real applications and feedback for more research and development are necessary and valuable, which also requires that social transportation systems must possess the mechanisms to access the feedback from traffic consumers.

The following illustrates the architecture of a crowdsourcing platform for transportation, which is deployed on cloud platform so that individual and organizations can take part in easily through (mobile) Internet, as shown in Fig. 3. The public can use it to release or acquire travel-related information according whenever needed. The information that social transportation system collects can be divided into four categories: 1) emergency events, such as road or subway accident, 2) guidance information, such as traffic congestion and road works, 3) travel-related information, like new marketplaces and joint travel notice, 4) sharable travel resource, like car-sharing and car-borrowing. Such information can be filtered and sent to the public or specific members in individual's social networks. Among them, we are more interested in the travel-related information, as it can affect individual's travel decision and behavior from different aspects, such as travel destination

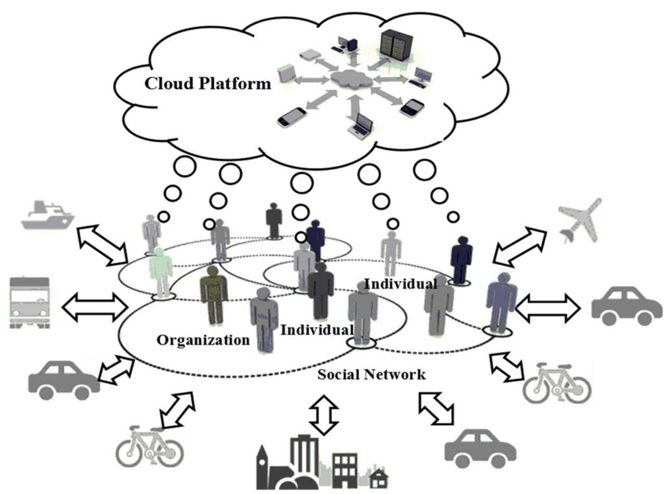


Fig. 3. The general process of generation and dissemination of social signal.

selection, travel route choosing, travel mode choosing, and travel plans (cancel planned travel or choose new travel).

On the other hand, the crowdsourcing platform can also be treated as a specified kind of social sensing network. Transportation management government can use it to capture social emergency events, policy feedback, and traffic sentiment, and adopt more detailed management through increasingly intelligent devices, like mobile phones. As a result, the service level of the whole transportation system can be improved. It is clear that the implementation of such platform must depend on the emerging advanced concepts, methods and technologies, such as big data, cloud computing and mobile Internet.

IV. ITS Clouds and Services

Cloud computing caters to the idea of "local simple, remote complex" in parallel traffic systems and can help us to organize computing experiments for testing the performance of different traffic strategies. Thus, only the optimum traffic strategies will be used in urban-traffic control and management systems. This helps enhance urban-traffic management system performance and minimizes the system's hardware requirements to accelerate the popularization of parallel traffic systems. We propose urban-traffic management systems using intelligent traffic clouds to overcome the issues we've described so far. With the support of cloud computing technologies, it will go far beyond other multiagent traffic management systems, addressing issues such as infinite system scalability, an appropriate agent management scheme, reducing the upfront investment and risk for users, and minimizing the total cost of ownership.

A. ITS Clouds

Agent-based traffic control can take advantage of the autonomy, mobility, and adaptability of mobile agents in handling dynamic traffic environments. Comparing to traditional control methods and strategies, where the control algorithms are static, the agents in the devices of PTMS can be modified and replaced in real time according to the surrounding traffic status. So the performance and the flexibility of the system are improved significantly. However, a large number of mobile agents will lead to a complex organization layer that requires enormous computing and power resources. If the requirement cannot be satisfied, either the traffic control agents cannot exert their advantages in diversity, or the whole system will fall into chaos and finally be paralyzed. One approach to satisfy the requirement is to add high performance computers, such as storage servers and computing servers, in the control center. As the system range and the running time is expanding, more and more servers need to be installed and the cost will increase rapidly. To conquer this problem, ITS clouds are designed for traffic control system. Using ITS clouds, complex computing and massive data storage can be stored in clouds, so higher performance can be achieves in lower cost.

The architecture of ITS clouds is implemented based on mobile agent and cloud computing technologies. All the traffic control agents are developed as software as a service (SaaS) and they can move in the network. The controllers and other field devices provide host environment for agents and they only store one or two agents for current traffic status. When the traffic status changes and current agents are no longer suitable, one new agent will move to the devices and replace the old one. This mechanism, which is called as local simple, remote complex (LSRC), is one well known idea to develop intelligent systems in networked environment. Taking advantage of the facilities provided by ITS clouds, the manufactures of the control devices and the developers of the systems can maintain and update the agents in remote center conveniently.

The architecture of ITS clouds is composed of four layers, which are application layer, platform layer, unified resource layer and physical layer. ITS clouds enable the traffic control system to be an open and extensible system, i.e., new control algorithms can be applied conveniently, without having to worry about updating the hardware of the controllers. Control center can also utilize the services provided by ITS clouds to optimize the traffic control agents and improve the performance of the whole system. As ITS clouds expand and improve, in the future, traffic management systems for different cities can be connected to form the intercity cloud, which will bring great convenience for data storage, data sharing, and data analysis [32].

The main advantage of ITS clouds is its scalability, i.e., can be extended infinitely. Based on ITS clouds, the computing ability and storage space can be enhanced according to the user's demands. Not only the computing and storage requirement of huge data for traffic control can be satisfied, but also the high performance computing of large-area traffic simulation for system testing can be implemented. In ITS clouds, services in different levels are packaged in unified interface for users outside the clouds. Currently, all the control algorithms in PTMS are packaged into control agents according to Foundation for Intelligent Physical Agents (FIPA) standards. Finally, the services in ITS clouds can be dispatched according to actual demand, which is implemented by reconfigure the resources in the clouds according to the requirement of traffic environment.

B. Traffic Flow Prediction Service Using Massive Traffic Flow Data

One important usage of ITS clouds is to provide traffic information services by predicting traffic flow based on cloud computing and big data analysis. As more and more detection technologies have been utilized in collecting traffic information, the content of the traffic information are getting much richer, and the detection range are getting much wider. All these cause the amount of data increasing rapidly. Facing that historical traffic data continue to accumulate, massive traffic detector data provide both opportunities and challenges for the optimization of traffic control systems. Here, we introduce how we conduct traffic flow prediction based on MapReduce framework.

The process of conducting traffic flow predicting based on MapReduce framework consists of three steps: model selection, parameter estimation and model combination. We will describe these steps in details in the following.

1) Model Selection: Traffic flow detector data can be described by multivariate Gaussian mixture model, which is composed of several weighted Gaussian probability density models. The Gaussian mixture model with M variables can be expressed as follows:

$$P(X|\Theta) = \sum_{i=1}^{M} \omega_i p_i(X|\theta_i).$$

Where X is the data set, p_i is the probability density for the ith variable, θ_i is the parameter vector for the ith variable, ω_i is the mixture weight for the ith variable, satisfying $\omega_i > 0$, $\sum_{i=1}^{M} \omega_i = 1$, $\Theta = (\omega_1, \ldots, \omega_M, \theta_1, \ldots, \theta_M)$ is the parameter set for the Gaussian mixture model.

2) Parameter Estimation: EM algorithm is one widely used method for parameters estimation. Using this method, the computation complexity of maximum likelihood estimate (MLE) can be greatly reduced, while the accuracy of the estimation is close to MLE. EM algorithm includes two steps: an expectation step (E-step) and a maximization step (M-step). The responding degree is calculated in E-step using current parameters, while the parameters are updated in M-step according to the responding degree. For one M-variable Gaussian mixture model, in which data set is $X = \{x_1, \ldots, x_N\}$ and the parameters are $\Theta_l = (\mu_l, \sigma_l), l = 1, \ldots, M$, one iteration of the EM algorithm is shown as follows:

E-step:

$$P(l|x_i, \Theta) = \frac{p\left(x_i|\Theta_l^{\text{old}}\right) * \omega_l^{\text{old}}}{\sum_{j=1}^{M} p\left(x_j|\Theta_l^{\text{old}}\right) * \omega_l^{\text{old}}}.$$

M-step:

$$\omega_l^{\text{new}} = \frac{1}{N} \sum_{i=1}^{N} P(l|x_i, \Theta)$$
$$\mu_l^{\text{new}} = \frac{\sum_{i=1}^{N} x_i * P(l|x_i, \Theta)}{\sum_{i=1}^{N} P(l|x_i, \Theta)}$$
$$\sigma_l^{\text{new}} = \frac{\sum_{i=1}^{N} P(l|x_i, \Theta) * (x_i - \mu_l^{\text{new}}) * (x_i - \mu_l^{\text{new}})^T}{\sum_{i=1}^{N} P(l|x_i, \Theta)}.$$

The EM algorithm will terminate if the preset iterations are finished or the convergence condition is satisfied. Once the EM terminate, the local traffic flow model for each data node is generated.

3) Model Combination: The local traffic flow models that generated by EM algorithm should be combined to form the global model for traffic flow prediction. First, the similarity of different local models is computed. Second, the local models are classified. Finally, the local models are combined to form global model according to the weight of each class.

Let C_1, C_2 be to local models, the distance between the two models can be calculated using the following formula:

$$DLM(C_1, C_2) = \frac{1}{MS(C_1, C_2)}.$$

Where,

$$MS(C_1, C_2) = \sum_{i=1}^{d} \int_{-\infty}^{+\infty} N_{\mu_1^i, \Sigma_1^i}(\overrightarrow{x}) * N_{\mu_2^i, \Sigma_2^i}(\overrightarrow{x}) d\overrightarrow{x}.$$

If two local models are close from each other, the similarity between them is high. Then the classification problem of the local models can be expressed as a minimum spanning tree problem, which can be resolved using Kruskal algorithm. Let the weight, mean value, covariance matrix of local models be expressed as $\omega_{l,M} = \{\omega_1, \ldots, \omega_n\}$, $\mu_{l,M} = \{\mu_1, \ldots, \mu_n\}$, $\sigma_{l,M} = \sigma_1, \ldots, \sigma_n$, respectively. The following function is used to judge which set the model C_i belongs to:

$$J(C_i, k) = \begin{cases} 1, & C_i \in C_K \\ 0, & C_i \notin C_K. \end{cases}$$

Let the data sample for local model C_i be $\rho(C_i)$. If the data sample sizes of the local models are not equal, the weight, mean value, covariance matrix of the final global models can be calculated according to the following formulas:

$$\omega_k = \frac{\sum_{i=1}^{n} \omega \cdot \rho(C_i) \cdot J(C_i, k)}{\sum_{i=1}^{n} \omega \cdot \rho(C_i)}$$
$$\mu_k = \frac{\sum_{i=1}^{n} \omega_i \cdot \rho(C_i) \cdot \mu_i \cdot J(C_i, k)}{\sum_{i=1}^{n} \omega_i \cdot \rho(C_i) \cdot J(C_i, k)}$$
$$\mu_k = \frac{\sum_{i=1}^{n} \omega_i \cdot \rho(C_i) \cdot \sigma_i \cdot J(C_i, k)}{\sum_{i=1}^{n} \omega_i \cdot \rho(C_i) \cdot J(C_i, k)}.$$

C. The Implementation Based on MapReduce

In the following, we will show some details of the implementation based on MapReduce. Before the implementation, the road map should be transferred into one directed graph, in which the arcs and the vertices represent the roads and the intersections respectively. Each arc is marked using two numbers, the capacity and the current traffic volume of the road, which are derived in a particular sampling moment from computational experiments. First, we need to input records that each holds an arc of the graph and its information. Then, for each arc record, the map operation emits two records, one keyed under each of the vertices that form the arc. The value of every record contains path (in the form of node pair) and augmenting flow (Δf). Each augmenting flow equals capacity minus volume. After this process, a series of bins are created, each of which holds records for every arc adjacent to its associated vertex. When it comes to the reduce phase, those records with the same key created in the map phase are put together by partition to search the path and calculate augmenting flow. Up to now, all the 2-distance paths between node pairs from the output of the reduce operation are generated. In the second round map and reduce operation, raw arcs and output of the last reduce are combined to form the input file. Similarly, the map process generates a series of records. Again, records with the same key are prepared for a particular reducer. So all the 3-distance (not only, perhaps longer) paths and the augmenting flows are calculated after this round. Similarly, we can start the third round, the fourth round and so on. It should be noted that during each round, loops must be excluded for their interference on obtaining the correct results. The iteration process is repeated until the outputs of two reduce operations are identical. This means that the paths and their augmenting flows between each node pair are contained in all of the outputs generated by each round reduce. All we need to do is to sort these results by node pair and augmenting flow.

V. Case Study

A. Background Introduction

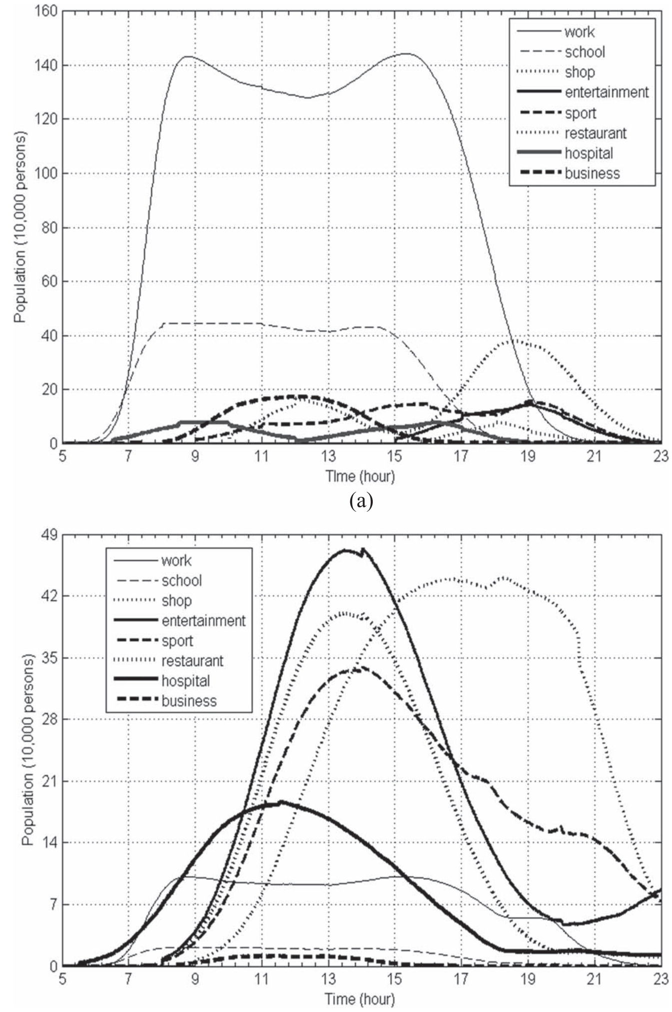
One case study has been carried out in Qingdao, Shandong province, China. Though the project is still under construction, some significant effects have been achieves, and we will introduce them briefly in the following.

The construction area in our case study covers five districts, which are Shinan District, Shibei District, Sifang District, Licang District and Laoshan District. The road network in the construction area covers 5 longitudinal main roads, 6 lateral main roads and 7 shopping centers. According to the construction plan, 300 intersections will be updated will new control devices, and among these intersections, 274 will adopt adaptive control functions. Meanwhile, 1560 spots will be equipped with traffic flow detectors and 68 traffic variable message signs will be installed.

B. Constructing the Artificial Transportation System

While carrying out the constructions of the actual system, the building of the artificial transportation system for Qingdao is also started. According to the fifth census in 2010 in China, the population in the constructing area amount to 2 457 400. We generate travel plans for each individual in this area. In the artificial transportation system, each individual is modeled as one agent. The travel demand of one agent is generated based on his activity plan. While all the agents are traveling and interacting in the virtual environment, the artificial transportation system grows up in a natural way.

The distributions curves of the artificial population carrying out different activities in workday and weekend are shown in Fig. 4(a) and (b) respectively. Fig. 4(a) is the distributions in one workday. It can be seen that the distributions of persons doing



(a)
(b)

Fig. 4. The distribution of population carrying out different activities in one day. (a) Workday. (b) Weekend.

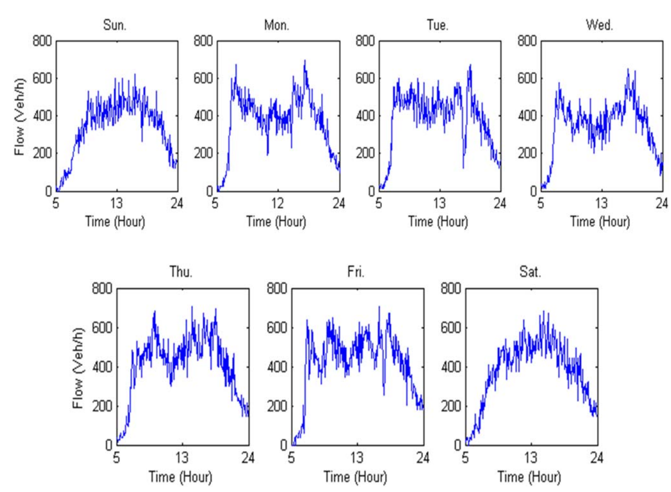


Fig. 5. Artificial traffic flows on through lines in four directions.

“work” and “school” are more regular than that of persons doing other activities. In addition, most people do “work” or “school” in daytime and the population that do other activities are very small until 6:00 PM. Fig. 4(b) is the distributions in weekend and, comparing to Fig. 4(a), there are significant

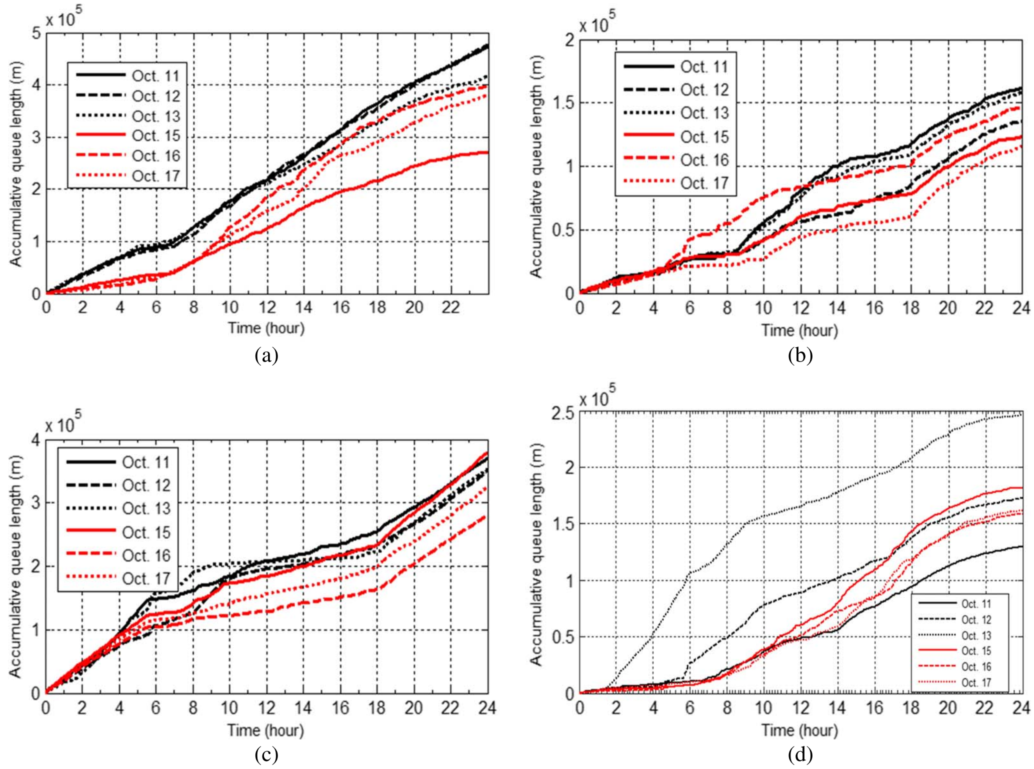


Fig. 6. The comparisons of the queue lengths on the straight lines in the four directions. (a) East. (b) South. (c) West. (d) North.

differences. In Fig. 4(b), as more people do discretionary activities (including shop, sport, eating out and entertainment) in weekend, not only these activities' frequencies increase sharply, but also their time ranges are extended notably. Clearly, the results in Fig. 4 are consistent with the reality very well. Intuitively, School and work are regular activities and their times are usually limited between 8:00 AM and 6:00 PM, while other activities are more flexible and individuals have more freedom to schedule them.

Fig. 5 shows the traffic flow data of one detector in the artificial transportation system from Monday to Sunday. We can see that the traffic flows curves in weekday usually have M shape, and the morning peak and evening peak are all very notable. It is also clear that the artificial traffic flows in weekend do not have morning or evening peak. Clearly, these results that generated by the artificial transportation systems have the same characteristics with the actual traffic flows.

C. Optimizing and Planning Based on PTMS

After the parallel transportation system has been established, computational experiment is carried out by connecting the actual system and the artificial systems. The execution of transportation computational experiment includes the following steps:

1) Utilizing various sensors to collect relevant data in real time in the actual transportation system, and generating one feasible solution by the parallel transportation system.
2) Building new solutions by adjusting the parameters of the original solution within small intervals.
3) Testing all the new solutions and the original solution in parallel transportation system, selecting the best solution.
4) Applying the best solution in the actual transportation system, observing the execution performance and evaluating the solution according to one specific standard. The specific standard, which is depended on the interests of the operators, can either one index or the weighted sum of several indexes.
5) Deciding whether the operator needs to update current solution based on the evaluation result of the sensing data from the actual system.

To make computational experiment one effective tool for studying complex systems, a set of feasible methods based on emerge, both for observing and analysis, has been established. The applications of recently proposed concept, emergent computation, have provided some ideal cases for us. The work in this area has been carried out in three aspects: first, for the instinct emerge, such as emerge one new structure, common statistics methods and various computational intelligence algorithms are adopted; second, for the pattern emerge in the original system, pattern recognize algorithms and data mining methods are adopted; for other essential emerge, such as the influence between the original system and new pattern, artificial intelligence methods for specific systems have been adopted. In this direction, some research and applications are under developing and initial results have been obtained [21].

Computational experiments on PTMS provide us the effective tools to carrying out optimization. Before demonstrating the optimization result, we will give a very brief introduction of the principles adopted in the actual system. According to

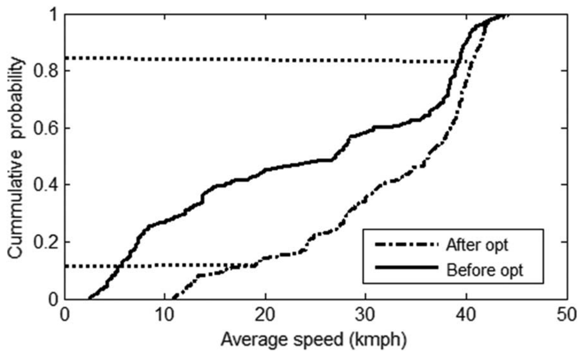


Fig. 7. Effectiveness of the optimization.

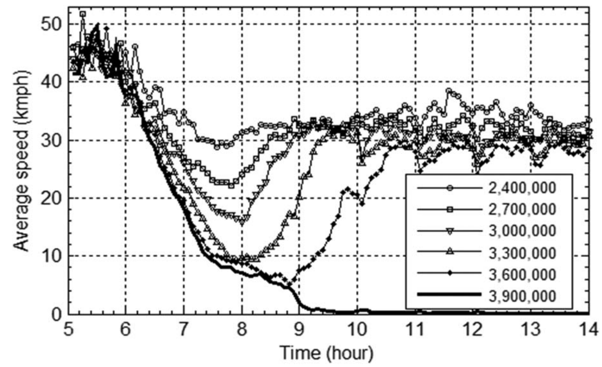


Fig. 8. Future prediction.

different control methods and different traffic conditions, the network is divided into control subarea by the relations among the intersections: 1) balance control methods are suitable for the area that includes several very congested intersections; 2) bottle control methods are suitable for single very congested intersection; 3) increasing-capacity control methods are suitable for quite congested areas; and 4) coordinated control methods and passage control methods are suitable for less crowded areas.

After 6 months of the deployment of PTMS-Qingdao, arterial travel time and the number of vehicle stops on arterial streets reduced 20% and 45%, respectively. Congestion miles of major key roads reduced 30%, travel time reduced 25%, and travel efficiency improved 43.39%.

Here we use one intersection located at the interchange of Shandong Road and Donghai Road as an example. The optimization of the control plans for this intersection has been finished in Oct. 14, 2014. The comparisons of the queue lengths on the straight lines in the four directions are shown in Fig. 6. The queue lengths from October 11th to 13th are collected before the optimization, while the queue lengths from October 15th to 17th are collected after the optimization. We can see that, after the optimization, the queue lengths in the four directions are all decreased, though the optimization effects are different in the four directions. The improvements of the traffic flow in east [Fig. 6(a)] and north [Fig. 6(d)] are more obvious than those in south [Fig. 6(b)] and west [Fig. 6(c)]. It should be pointed out that the queue lengths of Oct. 13 in Fig. 6(d) may be abnormal, because they are too higher than the other days. It may be caused by two reasons, one is that the traffic demand in that day was special, the other is that the detector in that the detector was not working properly.

The distribution curves of the average speed in two days before (Aug. 26, Tuesday) and after the optimization (Sep. 23, Tuesday) are shown in Fig. 7, respectively. We can also see that the traffic flows have been improved significantly after the optimization. The 15% and 85% quantiles, which are common indices used in urban traffic evaluations are also labeled using the dashed lines in this figure. The 15% quantiles of before and after optimization are 6.53 kmph and 21.2 kmph, respectively. The improvement is about 225%. The 85% quantiles of before and after optimization are 39.43 kmph and 40.73 kmph, respectively. The improvement is about 3%.

Based on parallel transportation systems, we can not only optimize the current system, but also predict the future development. Fig. 8 shows the prediction results of the average speed in the network when the populations are increased from 2 400 000 to 3 900 000. We can see that when the population reached 3 900 000, the traffic will be chaotic. This means 3 900 000 is the maximum population that can be accommodated in this area according to current infrastructures.

VI. Conclusion

In this paper, a new mechanism for the management and control of transportation systems, namely parallel transportation management and control system, is proposed. The new mechanism is the result of the integration and fusion of latest advanced technologies, including social signal, agent control, IoT, etc. ACP approach involving modeling with artificial systems, analysis with computational experiments, and operation through parallel execution for control and management of complex systems, provide the solid theory foundation for the new mechanism. Social transportation and cloud computing platform are two important aspects of the new mechanism. Our research and development efforts are still in the initial stage, though some verification has been finished. We believe that these efforts will eventually lead to a satisfactory answer to the long-standing question "Where is the Intelligence in ITS?" and, thus, contribute to the establishing of the next-generation intelligent transportation systems.

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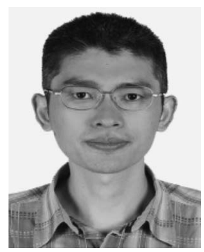
References

[1] A. Zanella *et al.*, "Internet of Things for smart cities," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, Feb. 2014.
[2] F.-Y. Wang and S. Tang, "Artificial societies for integrated and sustainable development of metropolitan systems," *IEEE Intell. Syst.*, vol. 19, no. 4, pp. 82–87, Jul./Aug. 2004.
[3] P. Liu and Z. Peng, "China's smart city pilots: A progress report," *Computer*, vol. 47, no. 10, pp. 72–81, Oct. 2014.

[4] Nanjing Mobile Extends 4G Public Transportation Points to 1,800 Vehicles in the City, D1net, Aug. 2013. [Online]. Available: www.d1net.com/scity/vindustry/traffic/232517.html
[5] P. Derler, E. A. Lee, and A. S. Vincentelli, “Modeling cyber-physical systems,” *Proc. IEEE*, vol. 100, no. 1, pp. 13–28, Jan. 2012.
[6] Y. Tan, M. C. Vuran, and S. Goddard, “Spatio-temporal event model for cyber-physical systems,” in *Proc. IEEE 29th Int. Conf. Distrib. Comput. Syst. Workshops*, Montreal, QC, USA, 2009, pp. 44–50.
[7] R. A. Thacker, K. R. Jones, C. J. Myers, and H. Zheng, “Automatic abstraction for verification of cyber-physical systems,” in *Proc. 1st Int. Conf. Cyber-Phys. Syst.*, New York, NY, USA, 2010, pp. 12–21.
[8] M. C. Bujorianu, M. L. Bujorianu, and H. Barringer, “A unifying specification logic for cyber-physical systems,” in *Proc. IEEE 17th Mediterranean Conf. Control Autom.*, Thessaloniki, Greece, 2009. pp. 1166–1171.
[9] F.-Y. Wang, “The emergence of intelligent enterprises: From CPS to CPSS,” *IEEE Int. Syst.*, vol. 25, no. 4, pp. 85–88, Jul./Aug. 2010.
[10] F.-Y. Wang, “Toward a revolution in transportation operations: AI for complex systems,” *IEEE Intell. Syst.*, vol. 23, no. 6, pp. 8–13, Nov./Dec. 2008.
[11] F.-Y. Wang, “Toward a paradigm shift in social computing: The ACP approach,” *IEEE Intell. Syst.*, vol. 22, no. 5, pp. 65–67, Sep./Oct. 2007.
[12] F.-Y. Wang, “Parallel control and management for intelligent transportation systems: Concepts, architectures, and applications [J],” *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 630–638, Sep. 2010.
[13] N. Zhang, F. Y. Wang, F. H. Zhu, D. B. Zhao, and S. M. Tang, “DynaCAS: Computational experiments and decision support for ITS,” *IEEE Intell. Syst.*, vol. 23, no. 6, pp. 11–15, Nov./Dec. 2008.
[14] Q. Miao *et al.*, “A modeling and computing platform of artificial transportation systems based on game engine,” *IEEE Trans. Intell. Trans. Syst.*, vol. 12, no. 2, pp. 343–353, Jun. 2011.
[15] G. Xiong *et al.*, “Parallel traffic management for 2010 Asian Games,” *IEEE Intell. Syst.*, vol. 24, no. 5, pp. 81–85, May/Jun. 2010.
[16] F. Zhu, S. Chen, Z.-H. Mao, and Q. Miao, “Parallel public transportation system and its application in evaluating evacuation plans for large-scale activities,” *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 4, pp. 1728–1733, Aug. 2014.
[17] B. Ning, H. Dong, D. Weng, L. 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.
[18] B. Ning *et al.*, “An introduction to parallel control and management for high-speed railway systems,” *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 1473–1483, Dec. 2011.
[19] C. Chen, F. Zhu, and Y. Ai, “A survey of urban traffic signal control for agent recommendation system,” in *Proc. 15th Int. IEEE ITSC*, 2012, pp. 327–333.
[20] F. Zhu, G. Li, Z. Li, C. Chen, and D. Wen, “A case study of evaluating traffic signal control systems using computational experiments,” *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 1220–1226, Dec. 2011.
[21] F.-Y. Wang, “Scanning the issue and beyond: Computational transportation and transportation 5.0,” *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 5, pp. 1861–1868, Oct. 2014.
[22] F.-Y. Wang, “Agent-based control for networked traffic management systems,” *IEEE Intell. Syst.*, vol. 20, no. 5, pp. 92–96, Sep./Oct. 2005.
[23] F.-Y. Wang, K. M. Carley, D. Zeng, and W. J. Mao, “Social computing: From social informatics to social intelligence,” *IEEE Intell. Syst.*, vol. 22, no. 2, pp. 79–83, Mar. 2007.
[24] F.-Y. Wang, “Social computing: Concepts, contents, and methods,” *Int. J. Intell. Control Syst.*, vol. 9, no. 2, pp. 91–96, 2004.
[25] D. Li *et al.*, *The Sociology of Transportation*. Beijing, China: China Soc. Sci., 2012.
[26] F.-Y. Wang, “A framework for social signal processing and analysis: From social sensing networks to computational dialectical analytics,” *Sci. Chin. Inf. Sci.*, vol. 43, no. 12, pp. 1598–1611, 2013.
[27] F.-Y. Wang, “Scanning the issue and beyond: Real-time social transportation with online social signals,” *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 3, pp. 909–914, Jun. 2014.
[28] 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. 13, no. 4, pp. 1–10, Mar. 2013.
[29] S. Chen, F. Zhu, and J. 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.
[30] J. Cao and K. Zeng, “Web-based traffic sentiment analysis: Methods and applications,” *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 2, pp. 844–853, Apr. 2014.
[31] K. Zeng, W. Liu, X. Wang, and S. Chen, “Traffic congestion and social media in China,” *IEEE Intell. Syst.*, vol. 28, no. 1, pp. 72–77, Jan./Feb. 2013.
[32] Z. Li, C. Chen, and K. Wang, “Cloud computing for agent-based urban transportation systems,” *IEEE Intell. Syst.*, vol. 26, no. 1, pp. 73–79, Jan./Feb. 2011.



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