Parallel Control and Management for Intelligent Transportation Systems: Concepts, Architectures, and Applications

Fei-Yue Wang, *Fellow, IEEE*

***Abstract*—Parallel control and management have been proposed as a new mechanism for conducting operations of complex systems, especially those that involved complexity issues of both engineering and social dimensions, such as transportation systems. This paper presents an overview of the background, concepts, basic methods, major issues, and current applications of Parallel transportation Management Systems (PtMS). In essence, parallel control and management is a data-driven approach for modeling, analysis, and decision-making that considers both the engineering and social complexity in its processes. The developments and applications described here clearly indicate that PtMS is effective for use in networked complex traffic systems and is closely related to emerging technologies in cloud computing, social computing, and cyberphysical–social systems. A description of PtMS system architectures, processes, and components, including OTS*t*, Dyna*CAS*, *a*DAPTS, *i*TOP, and TransWorld is presented and discussed. Finally, the experiments and examples of real-world applications are illustrated and analyzed.**

***Index Terms*—ACP, cloud computing, cyberphysical–social systems (CPSS), data-driven decision making, parallel control, parallel management, traffic control and management.**

I. Introduction

OVER the last three decades, we have witnessed the initiation, development, deployment, and tremendous growth of intelligent transportation systems (ITS) and their significant impact on our life and society. Today, transportation research and development is no longer a field dominated by civil, mechanical, operations research, and other traditional engineering and management disciplines. Rather, computer sciences, control, communication, the Internet, and methods developed in artificial intelligence (AI), computational intelligence, web sciences, and many other emerging information sciences and engineering areas have formed the core of new ITS technology and become integral and important parts of modern transportation engineering.

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The author is with the Key Laboratory of Complex Systems and Intelligence Science, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China (e-mail: feiyue@ieee.org).

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However, we have experienced a few "road bumps" over the last few years in ITS research and applications, especially in relation to system-level traffic control and management. This can be verified from the distribution of papers which have appeared in the ITS flagship publication IEEE Transactions on Intelligent Transportation Systems (T-ITS). As indicated by recent analysis [1]–[4], of the four most active research topics that has emerged in T-ITS over the last decade, the two traffic-related topics (i.e., management and surveillance) led the trend before 2005 and were subsequently taken over by the two vehicle- and vision-related topics. The percentage of papers published on traffic-related research has dropped from 60.16 (2000–2004) to 22.34 (2005–2009), while papers about the vehicle and vision have increased from 27.64 to 35.10 during the same time period. However, the situation has deteriorated in the last two years: of the 118 papers we published after 2008, only 24 were traffic related, and none addressed system-level traffic control or management. Other publications were mostly focused on vehicle-related research and applications.

While research and development (R&D) in vehicular technology is extremely important and useful, we must put more intensive effort into traffic control and management research as the urban congestion problem is becoming an increasingly major issue in social, economic, and environmental concerns around the world, from developed countries to emerging new powers. To overcome current "road bumps" and speed up the research and development (R&D) effort in traffic control and management, particularly at the system level, we need new thinking and a multidisciplinary approach.

Recent R&D advancements in complexity, complex systems, and the intelligence sciences have provided us an opportunity to look into new methods of conducting intelligent traffic control and management from new perspectives, at the system level with new tools, and an integrated approach. Actually, many efforts have already been made in this direction over the past two decades, ranging from the use of cellular automata in traffic flow modeling [5], [6], wide applications of data-mining techniques for traffic behavioral analysis [7]–[11], agent-based technology for traffic control [12], AI methods for assessing real-time highway traffic conditions, and transportation security [13]–[18]. Still, we need to coordinate our research and systematic effort with those emerging methods and techniques and hopefully they will eventually lead to a satisfactory answer to the long-standing question "Where is the Intelligence in ITS?"

In this paper, we present the overall approach and briefly describe our works and results over the past decade in the application of concepts and methods developed in complex systems and intelligence sciences for intelligent transportation, particularly ACP-based parallel control and management systems. An early version of this paper was originally planned for a 2005 Special Issue on Advanced Traffic Management Systems in T-ITS but was not published as scheduled. This current version has incorporated our most recent progress on the development and applications of Parallel transportation Management Systems (PtMS). Note that some of the results here have already been reported in some of the Chinese or nontransportation literature [19]–[31]. Finally, a short explanation on the meaning of "parallel": the term implies the parallel interaction between an actual transportation system and its corresponding artificial or virtual counterparts (one or often more) and not parallelism in the sense of parallel computing, where tasks or calculations are simultaneously divided and carried out. Of course, parallel computing can play an important role in the implementation of parallel control and management.

This paper is organized as the following: Section II introduces the basic concepts of ACP and artificial transportation systems (ATS) and their applications in ITS. Section III presents a brief description of the architectures and operations of PtMS. Section IV presents both the software and hardware platforms and systems for implementing PtMS, whereas Section V illustrates the results of two studies conducted in Jinan and Suzhou, China using computational experiments and field testing of PtMS, respectively. Section VI concludes the paper with remarks on future works and directions.

II. ACP-Based Parallel Control and Management

A. What Is the ACP Approach

The ACP approach was originally proposed in [19]–[21] for the purpose of modeling, analysis, and control of complex systems. Basically, this approach consists of three steps: 1) modeling and representation using *A*rtificial societies; 2) analysis and evaluation by *C*omputational experiments; and 3) control and management through *P*arallel execution of real and artificial systems. The complex systems considered in the ACP approach have two essential characteristics.

1) *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.
2) *Unpredictability*. Intrinsically, with limited resources, the global behaviors of a complex system cannot be determined or explained in advance at a large scope.

Many systems involving human and social behaviors display those two characteristics. They lead to three deductions.

1) We must take a holistic approach in dealing and modeling with complex systems. Artificial systems would be one of the most effective tools in representing such complex systems in a holistic fashion.

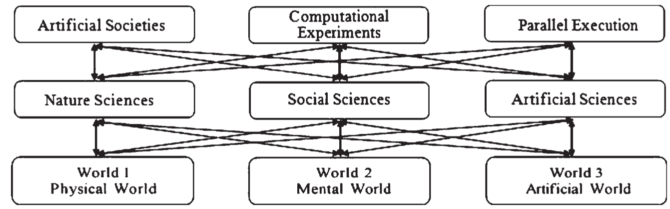


Fig. 1. Philosophical and scientific foundations of the ACP approach.

2) There are no fixed once-and-for-all solutions for problems in complex systems. Any effective and satisfiable solution should be adaptive and able to learn from its tasks and experiences. Computational experiments are essential in developing and supporting such solutions.
3) Generally, there are no optimal solutions for complex systems, let alone any unique optimal solution. Parallel execution provides an effective mechanism to implement various solutions, as well as evaluate, validate, and improve their performance.

The basic idea of the ACP approach is rooted in Popper's theory of reality, which states that our universe consists of three interacting worlds: World One, i.e., the physical world; World Two, i.e., the mental world; and World Three, i.e., the artificial world. Fig. 1 shows the philosophical and scientific foundations of the ACP approach.

B. Why Is ACP for ITS?

Clearly, real-world transportation systems, such as large-scale urban traffic systems, exhibit the two characteristics considered in the ACP approach. However, the main motivation behind employing ACP here is a lack of timeliness, flexibility, and effectiveness in the current operation management systems in transportation. Although, the introduction of ITS in transportation has greatly improved the situation, there is still much room for improvement. As often discussed, researchers are still facing the question "Where is the *intelligence* in ITS?"

The application of an ACP approach in transportation problems will significantly enhance and improve the reliability and performance of current ITS technology. In addition, it will provide an effective platform and an important vehicle to facilitate use of almost all the concepts and methods developed in the fields of AI and computational intelligence and thus inserting true intelligence in ITS. Fig. 2 presents the framework for ACP-based parallel control and management for transportation systems.

There are many other advantages of using the ACP approach in transportation. For example, both cyberphysical systems (CPS) and cloud computing are naturally embedded in this approach. As a matter of fact, CPS, as well as its extension, i.e., cyberphysical–social systems (CPSS) [22], is a special case of intelligent spaces and an extension of intelligent transportation spaces (ITSp); both were developed in our previous studies [23]. As for cloud computing, it has already been in use since the late 1990s in our work on agent-based control and management for networked traffic systems and other applications [24] under the design principle of "local simple, remote complex" for high intelligence/low cost smart systems. As recently pointed

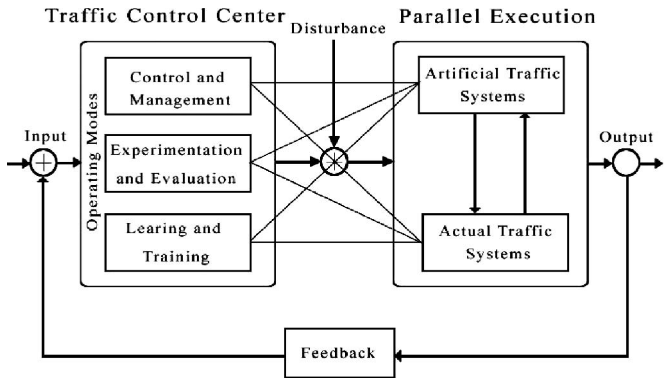


Fig. 2. Framework of the ACP-based parallel control and management for transportation systems.

out, the ACP offers a kind of cyberspace-enabled parallelism that could open a wide range of new application scenarios, such as future driving in intelligent transportation spaces for integrated and better traffic management, vehicular safety, energy efficiency, reduced pollution, and maintenance services, where vehicles, highways, roads, intersections, and operation centers are all embedded with various types of intelligent spaces, fixed in traffic operation centers, mobile on cars, mixed or hybrid at road intersections, etc. [22], [23].

C. ATS

The ACP approach originated from our studies of ATS in the late 1990s and early 2000s, which, in turn, were motivated by a lack of available large scale data this is verifiable, repeatable, and able to be manipulated for ITS research [25]–[27]. In the ACP approach, ATS provides the foundation for implementing the mechanism of parallel control and management in transportation systems.

Basically, ATS are derivatives of artificial societies and extended computer traffic simulation systems [27]–[29]. There are many differences between ATS and traditional traffic simulations. However, the two major ones are given here.

1) *Objective*. The objective of traditional traffic simulation is to represent or approach the true state of actual traffic systems, whereas the primary goal of ATS is to "grow" live traffic processes in a bottom–up fashion and provide alternative versions to actual traffic activities. In sociologist Adorno's words, ATS reveal traffic properties based on the belief that "only through what it is not will it disclose itself as it is" [28].
2) *Scope*. Normally, ATS must deal with a wide range of information and activities. Most of the current traffic simulation focuses on direct traffic-related activities alone, whereas ATS generates their traffic processes from various indirect facilities and activities, such as the weather, legal, and social involvements.

Fig. 3 describes the main component parts of ATS, which include traffic, logistic, construction, management, regulatory, social-economic, and environmental subsystems, as well as information, computational, and decision-making facilities. A detailed discussion of ATS and its related applications can be found in [25]–[27] and in the coming Special Issue on ATS in this journal March 2011.

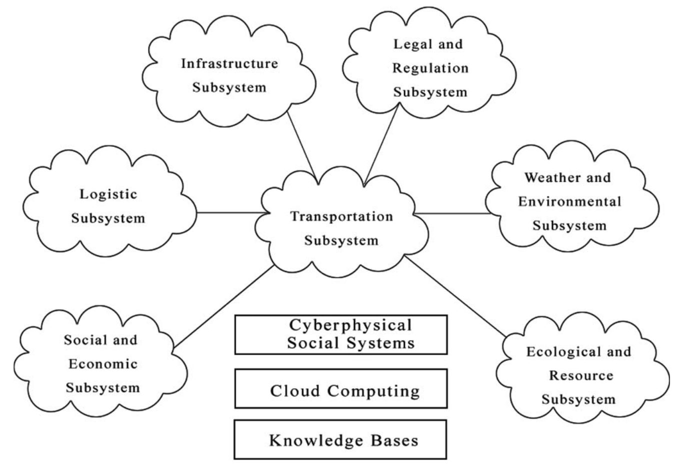


Fig. 3. Scope, framework, and facilities of ATS.

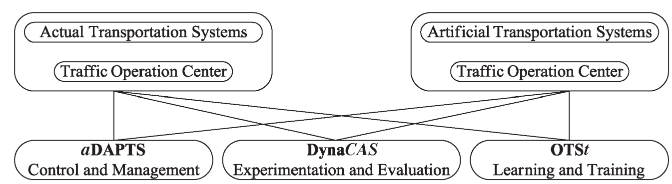


Fig. 4. System architecture and operation processes of PtMS.

III. System Architectures and Operation Processes

A. PtMS: System Architecture and Operation Processes

Fig. 4 presents the system architecture of ACP-based PtMS. It should be pointed out that normally, there is more than one ATS used in parallel traffic control and management. For example, different ATS can be created, respectively, for the purposes of historical traffic situations, normal and average performance, optimal and ideal operations, or worst-case scenarios for disasters and emergency management. Through interaction and parallel operations between an actual transportation system and its corresponding multiple ATS, the effectiveness of different traffic strategies under various conditions and expectations can be evaluated and analyzed, both offline and online, and useful information can be obtained timely and combined to generate and select decisions for control and management [30].

Typically, PtMS consist of five major components: 1) actual transportation systems; 2) ATS; 3) traffic operator and administrator training systems (OTS*t*); 4) decision evaluation and validation systems (Dyna*CAS*); and 5) traffic sensing, control and management systems (*a*DAPTS). The operation process of PtMS is based on the co-evolution of real systems and the corresponding ATS. The operation process can be divided into three modes: 1) training; 2) testing; and 3) operating. General operational procedures can be derived from the functional specification of operating systems OTS*t*, Dyna*CAS*, and *a*DAPTS in sequel. More information can be found in [24] and [30].

B. Training and Learning: OTSt

Operator Training Systems for transportation (OTS*t*) is developed for learning and training mode operations for traffic operators and administrators. The use of OTS*t* was partially inspired by the applications and success of operator training simulation in many other advanced and complex industrial operations, such as in petrochemical production processes. Task requirements and procedures for both regular traffic operations and emergency situations are incorporated into OTS*t* in order to make its functionality more useful and closer to reality. Sessions by OTS*t* can be generated manually by human operators or automatically by agent programs. Manual sessions are also used to collect behavioral data from trainees and learners. Using agent-based behavioral modeling, automatic sessions can be employed when conducting accelerated testing and evaluation on the reliability and effectiveness of traffic operational procedures and regulations.

C. Testing and Evaluation: DynaCAS

Dynamic network assignment based on Complex Adaptive Systems (Dyna*CAS*) is constructed to design, conduct, evaluate, and verify computational transportation experiments, detect existing and emerging traffic patterns, and support the use of advanced traveler information systems, advanced traffic-management systems, and other ITS modules [31]. Dyna*CAS* facilitates the estimation and predication of traffic network conditions, performance testing and evaluation of different traffic control and management measures and information dissemination strategies, and decision support to traffic operators and individual drivers. Using ATS, Dyna*CAS* is able to pay special attention to rule-based computational modeling of the social and behavioral aspects of people, vehicles, roads, and environments involved in transportation activities.

In addition to conventional microscopic, mesoscopic, and macroscopic specification, a level of logic representation has been introduced in Dyna*CAS* to represent the transportation networks so that factors in social and economic, ecological and resource, construction and infrastructure, logistical, legal, and regulatory aspects can easily be incorporated. On the logic level, transportation modeling extensively employs qualitative information in linguistic forms, and computing with words and methods in linguistic dynamic systems is used to achieve quantitative analysis. Data-mining techniques are also used to discover useful patterns from simulation results and computational experiments on all levels. Compared with other traffic estimation and predication systems (TrEPS), such as the well-known DynaSMART and DynaMIT, methods in AI and complex systems are much more extensively used in Dyna*CAS* to provide additional flexibility and efficiency in traffic-condition analysis and decision evaluation.

There are five major blocks in Dyna*CAS*: 1) data support; 2) experiment design; 3) traffic simulation; 4) decision generation; and 5) performance evaluation. Fig. 5 describes the overall framework and workflow of Dyna*CAS*.

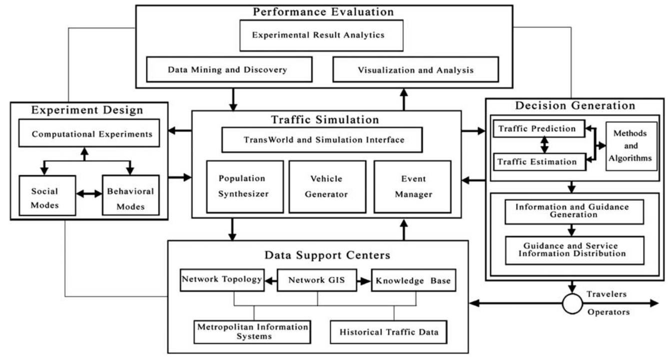


Fig. 5. Overall framework of Dyna*CAS*.

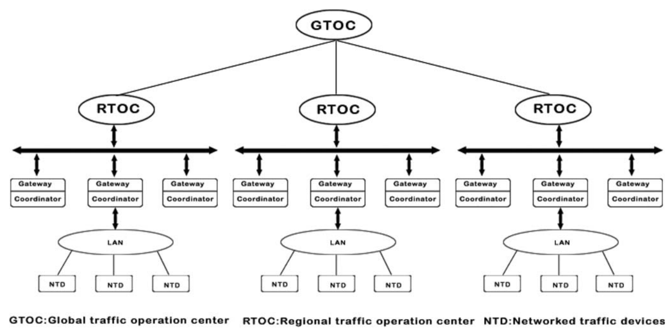


Fig. 6. Network architecture of *a*DAPTS.

D. Control and Management: aDAPTS

Agent-based Distributed and Adaptive Platforms for Transportation Systems (*a*DAPTS) is built to provide supporting and operating environments to design, construct, manage, and maintain autonomous agent programs for various traffic tasks and functions. Those agents are delivered to traffic-control centers, roadside controllers, sensing devices, and information systems via communication networks to make the right decisions and collect the right information at the right time. We have designed and manufactured special intersection light controllers and sensing systems that are capable of hosting and processing traffic-control agents for different functions.

Generally, an agent can autonomously move in networked environments, identify its tasks, and actively improve its performance. Transitioning from traffic-control and management algorithms to traffic-control and management agents is a natural step forward in this age of networks and connectivity. This step enables an intelligent and proactive mechanism that will significantly improve the performance and reliability of traffic operation control and management, yet it will have low cost for networked transportation systems.

Traffic task agents can be distributed at different operating centers and information sites. To ensure a coherent control and communication mechanism among those agents, we must integrate and coordinate their objectives and activities. A hierarchical intelligent control architecture consisting of organization, coordination, and execution levels has been used to facilitate the activities and operations of traffic agents. Fig. 6 presents

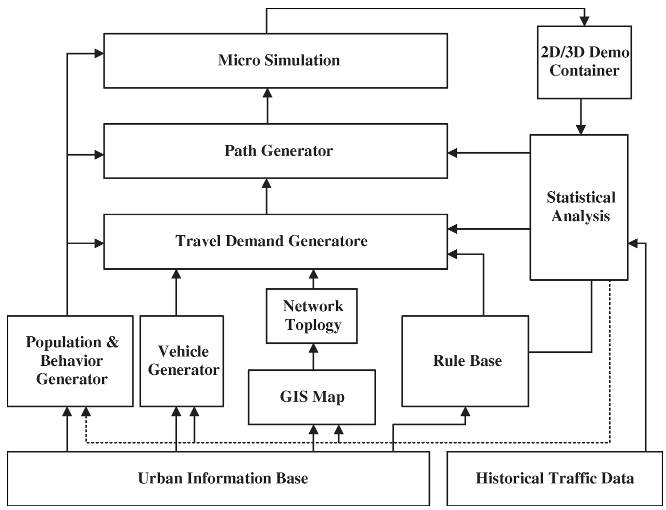


Fig. 7. System architecture and components of TransWorld.

the system architecture of *a*DAPTS in a distributed environment connected by wide-area networks (WAN) and local-area networks (LAN). In *a*DAPTS, a global traffic operating center (GTOC) (virtual or real) is designed to construct, organize, and maintain different types of agents for various traffic tasks, such as intersection light control, traffic-incident detection, and route guidance. WANs link the GTOC to several regional traffic-operating centers (RTOC), which host various agent repositories for regional demands and requirements of traffic control and management. RTOC coordinate and dispatch traffic agents to thousands of intersection light controllers, ad hoc networks, display devices, and guidance equipment at hundreds of locations. At each location, a gateway downloads task agents from WANs to traffic controllers, sensors, displayers, etc. through LANs and uploads information and requests from traffic devices to RTOC. Each location also has an agent coordinator to conduct cooperative control and management among traffic devices and within an individual device. A more detailed discussion of agent-based control and management of traffic systems can be found in [24].

Clearly, there is a natural link between PtMS and CPS, CPSS, and cloud computing. For example, CPS can be used to implement smart intersection traffic-control systems via *a*DAPTS, CPSS can be employed to build ATS in cyberspace and construct intelligent web-based Dyna*CAS* and OTS*t*, and cloud computing is a cost effective way to host and operate the entire PtMS.

IV. Software and Hardware Platforms

A. TransWorld: From Simulations to Experiments

TransWorld, which was developed by the Complex Adaptive Systems for Transportation (CAST) Laboratory, is a computer program designed to support the construction and validation of ATS. Fig. 7 shows TransWorld's system architecture and major components.

First of all, TransWorld is different from other existing computer traffic simulation programs in three aspects: 1) Similar to computer games, it can generate "artificial" traffic behaviors and other related data using only population statistics and behavioral models, which are very useful for testing and validation purposes in many transportation applications, particularly at the level of logic correctness. 2) It provides a hierarchical environment for integrating and exchanging information when traffic modeling and analysis at different resolutions, ranging from microscopic, mesoscopic, and macroscopic to logic emulations. 3) It offers a platform or a "living traffic laboratory" to conduct computational experiments for the analysis and synthesis of transportation systems. TransWorld is based on agent programming and object-oriented techniques for social and behavioral modeling. Clearly, the recipes and architectures developed for conventional traffic simulations, particularly those for TRANSIM, DynaSmart, and DynaMIT, are still extremely useful in the construction and operation of TransWorld.

Recently, an intensified effort has been launched to set up standards and procedures to construct model transportation systems (MTS) using an open-source version of TransWorld. The purpose is to establish open protocols and platforms, so that transportation researchers and practitioners around the world can join efforts, such as by crowdsourcing, to develop various MTS at different scales for testing, evaluation, and validation, as well as for serving as toolkits or repositories of recipes, standards, and architectures in transportation studies. Unlike conventional traffic-simulation programs, MTS is intended to run continuously in cyberspace through web computing and computer gaming technologies, just like real traffic systems in real cities. Similar to model economic systems, MTS can be an effective tool for the research, development, evaluation, and validation of real-world transportation solutions.

New initiatives on ATS and TransWorld, as well as issues in designing and coding related open-source systems through crowdsourcing, will be addressed at the upcoming Fourth IEEE International Workshop on ATS at Madeira Island, Portugal, on September 19–22, 2010. More information on TransWorld can be found in [29]–[31].

B. *i*TOP: Integrated Traffic Operation Platform

The actual control and management of traffic equipment and systems are carried out through the software platform *i*TOP, and the operating system of PtMS. Currently, the main purpose of *i*TOP is to support the operations and interactions between the actual traffic system, ATS, OTS*t*, Dyna*CAS*, and *a*DAPTS. In addition, *i*TOP provides five functions (see Fig. 8).

1) *Traffic data collection.* Traffic data is collected from related traffic databases, information systems, social media, floating probe vehicles, and sensing devices, such as induction loops and video cameras at intersections and roadsides. Normally, *i*TOP stores collected traffic data in a distributed database system.
2) *Traffic information processing.* All traffic data is processed, evaluated, classified, and analyzed by *i*TOP according to both predefined and online generated adaptive objectives. Useful traffic feature information is extracted from the general traffic data to concisely and precisely represent traffic conditions and support traffic control operations.

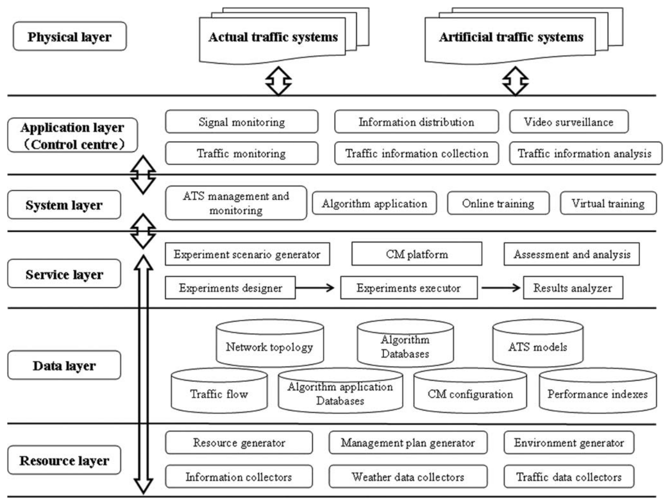


Fig. 8. Architecture and functions of *i*TOP.

3) *Traffic analysis and evaluation. i*TOP offers methods used to determine the levels of traffic services and calculate and compare various traffic indexes and measures according to regional or national standards. Results will be used for evaluation, assessment, improvement, decision support, and future transportation planning.
4) *Traffic information services. i*TOP offers information services for traffic-control operations and public sections. After fusing traffic information from its own databases and other sources, it distributes real-time and historical traffic information to decision makers for making social policies, transportation administrators and operators, travelers, and commerce vehicle operators for route guidance and mode selection.
5) *Traffic-control operations. i*TOP serves as an interface for operators and administrators to monitor traffic information and remotely manage and control traffic devices and equipment. In addition, it provides tools and real-time dynamic traffic information to regulate traffic flows for special needs and mass events (such as large-scale music concerts and sport games). *i*TOP also provides contingency traffic plans to handle accidents and support emergency management.

C. PtMS Experimental Station: Prototype Development

To facilitate the testing, evaluation, and validation of PtMS development, three versions of the PtMS Experimental Station have been built since 2006. Fig. 9 shows its most recent version V3.0, as completed and field tested in 2009.

A PtMS Experimental Station consists of five major parts: 1) *i*TOP supported traffic operating center for the actual traffic system; 2) *i*TOP-supported traffic operating center for artificial traffic systems; 3) agent-based intersection controllers, variable message systems, and vision-based traffic flow sensors for conducting hardware-in-loop traffic emulations; 4) traffic lights and display devices; and 5) servers and networks for cloud computing. Fig. 10 presents the agent-based traffic controller GreenPass V 5.0 and traffic-flow analyzer RoadScope; both were developed by CASIC Inc. and the CAST Laboratory since 1999.

Fig. 9. PtMS Experimental Station V 3.0.

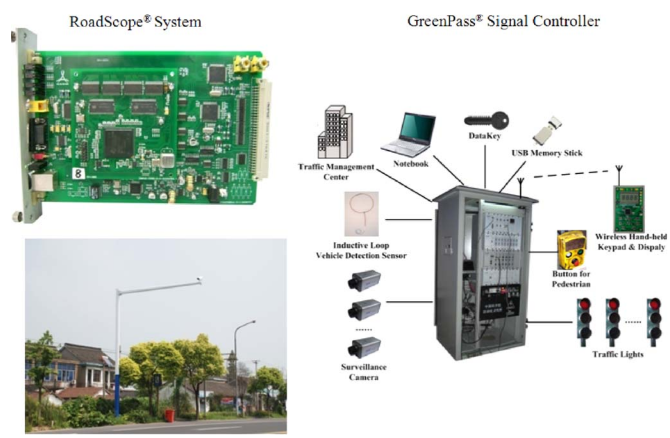


Fig. 10. RoadScope and agent-based traffic controller GreenPass V 5.0.

Fig. 11. Area of field study in Jinan for traffic computational experiments.

V. Experiments and Applications

A. Computational Experiments: Jinan Field Study

From 2004 to 2007, a field study on the effectiveness of ATS has been carried out in a district of Jinan city, which is the capital of Shandong Province and a populous region and a major economic power in northeast China.

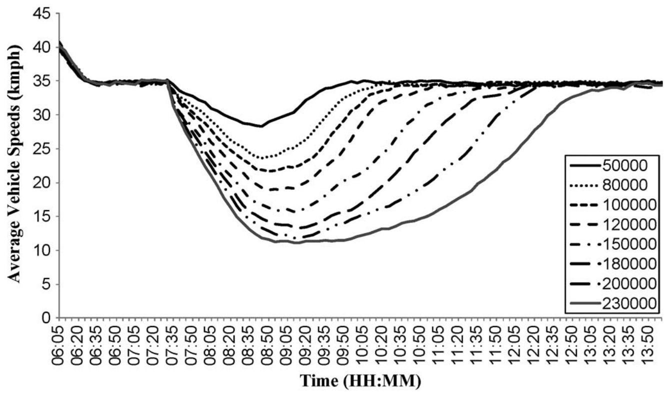


Fig. 12. Average speed of all vehicles in the traffic network of Jinan ATS.

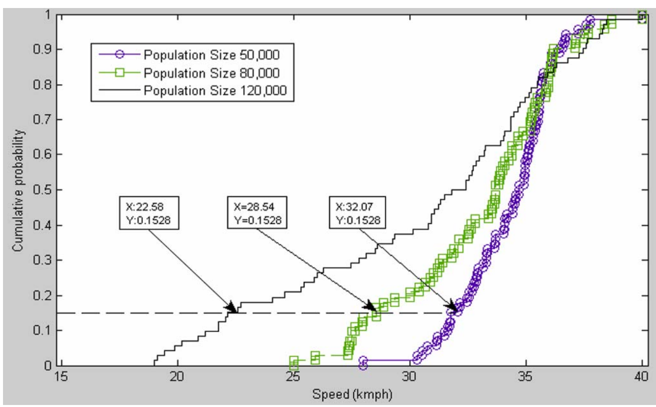


Fig. 13. Cumulative distribution curves of average vehicle speeds under different population sizes.

We have focused on the area within the second ring of the Jinan urban traffic arterial network. This selected area, which covers 255 km^2, east to Lishan Road, west to 12th Wei Road, south to 10th Jing Road, and north to Beiyuan Avenue, is the central business district of the city (see Fig. 11). The area includes 410 sites, which are directly related to traffic flow generation: 163 residential communities, 88 office buildings, 59 schools, 37 restaurants and hotels, 21 hospitals, 19 shopping malls, 13 recreational parks, and ten sport facilities. An ATS with 324 traffic nodes and 646 road links, which is called Jinan ATS, has been established using TransWorld specifically for this area, and various traffic computational experiments have been conducted based on Jinan ATS. Due to space limitations, we will only discuss the results from population pressure experiments. In this investigation, the population of the area, which was generated by an artificial population synthesizer, are increased from 50 000 to 230 000 at an interval of 10 000.

Fig. 12 presents the impact of the population on the average speed of vehicles driving within the traffic network of the selected area when regulated by a simple time of day (TOD) strategy. For the sake of clarity, we only show the results at the population levels of 50, 80, 100, 120, 150, 180, and 230 thousands, with their corresponding population densities at 196, 314, 392, 470, 588, and 706 person/km^2, respectively. As expected, the average speed of vehicles in the network is gradually decreased as the population is increased from 50 to 230 thousands. Note that the average speed minimum, which occurred during the morning peak, drops from about 28 km/h to about 10 km/h. Fig. 13 shows the cumulative distribution curve of average speeds under three population sizes, i.e., 50, 80, and 120 thousands, respectively. Three 15 quantiles of speed distributions, which are a common index used in urban traffic evaluation, are also marked in Fig. 13. Clearly, when the population size increases from 80 to 120, the corresponding quantile speed drops from 32.07 to 22.58 km/h, which is a 30% decrease. Variance analysis indicated that the differences described in Fig. 13 are statistically significant with a confidence level of 99.

Fig. 14. Area of field study in Taicang for PtMS.

B. Parallel Control and Management: Taicang Field Study

From 2008 to 2009, a field study on the effectiveness of PtMS was conducted in Taicang city of Suzhou, which is a major industrial metropolitan region and economic engine on the Yangztz Deltz in southeast China. Note that, historically, Taicang was a major harbor in China where Zheng He launched his first voyage to the West Ocean in the year of 1405.

The field study was conducted on Tailiu Road, which is a part of provincial highway S339. The area of interest was 8 km long and 2.2 km wide, stretching across the Taicang central business district (population 185 000), Ludu town (population 31 000), and Liuhe town (population 51 000). The current population of the selected area is close to 30 000. There are five major road intersections as shown in Fig. 14. To carry out the study and compare the performances of old and new systems, all existing traffic equipment was removed and replaced with new devices developed by the CASIC and CAST Laboratory. Both GreenPass V5.0 traffic controllers and RoadScope traffic flow sensors have been installed at the five intersections. The overall traffic operations were monitored and controlled by PtMS V3.0 both locally at the ZKZN ITS Laboratory in Suzhou and remotely at the CAST Laboratory in Beijing via a special WAN service provided by China Telcom.

An ATS was constructed using TransWorld, which is called Taicang ATS, for the selected area. Taicang ATS has incorporated traffic, social, commercial, and industrial facilities, as well as models of travel demands and behaviors in its emulation. With Taicang ATS, we are able to evaluate the performance of different traffic-control strategies and study the impact on traffic conditions by local population's social and economic activities. Before PtMS, Taicang was evaluating traffic-control strategies based on their actual performances, the preliminary evaluation processes normally takes weeks or even months—to complete, and the final selection of the operational strategy even longer.

TABLE I
PHASE ADJUSTMENT AND CHANGES IN GREEN TIMES AT INTERSECTION FEIHU

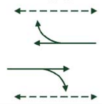
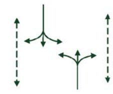
Phase Sequences		Ø1 	Ø 2 	Ø 3 
Original TOD Plan	Peak	40s	10s	20s
	Off Peak	35s	10s	15s
New Adaptive Plan	Peak	[40s,50s]	[10s,30s]	[20s,30s]
	Off Peak	[35s,50s]	[10s,30s]	[15s,30s]

TABLE II
OVERALL TRAFFIC PERFORMANCE IMPROVEMENT ON TAILIU ROAD

Evaluation Indices	**Changes**	
	Peak	**Off Peak**
Average Vehicle Speed	+ 9.2%	+ 15.3%
Average Vehicle Delay	- 21.4%	- 31.5%
Numbers of Stops	- 14.5%	- 28.2%
Queue Length	- 12.1%	- 17.3%
Arterial Capacity	- 21%	- 26.1%

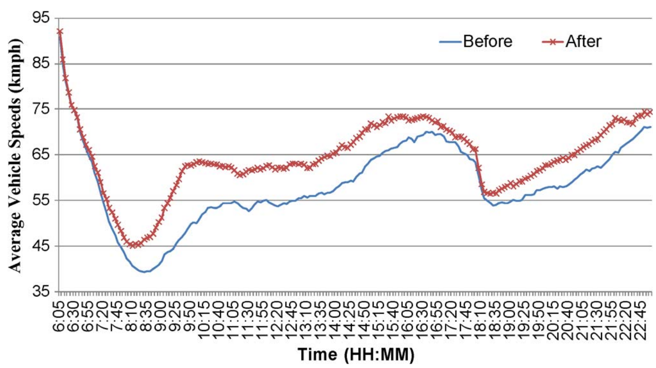


Fig. 15. Average vehicle speeds on Tailiu Road: before and after PtMS applications.

Based on Taicang ATS, we are able to implement a traffic-management system while testing evaluating and selecting the traffic-control strategy. PtMS has also greatly reduced the length of period required for adjusting and optimizing traffic-control parameters.

To compare the traffic performance before and after, Table I presents the green times at Intersection Feihu, whereas Table II summarizes the overall difference between traffic situations on Tailiu Road before and after the application of PtMS V3.0. Fig. 15 indicates a clear improvement in the average vehicle speed when driving in the selected area of study; the daily average vehicle speed has increased from 58.5 to 64.3 km/h, which is an 11% increase. Note that while the improvement during non-peak periods is significant the improvement is less obvious during the peak periods (6:30 A.M. to 8:00 A.M. and 16:30 P.M. to 18:00 P.M.). This is because traffic conditions are near the state of full congestion during the peak periods, and therefore, it is difficult to improve performance through traffic signal regulation alone.

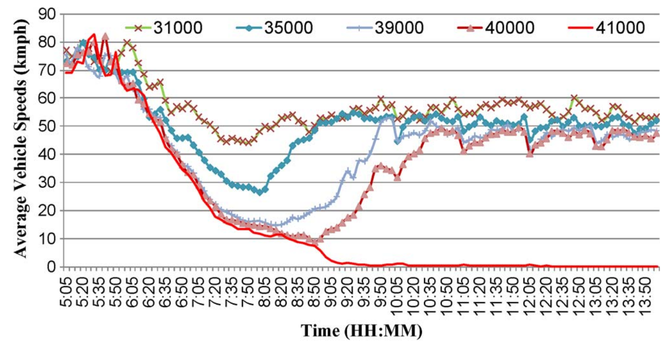


Fig. 16. Average vehicle speeds on intersection Feihu at population levels 31 000 to 41 000.

To investigate the impact on traffic by future population and activity growth in the selected area of study, a computational experiment has been designed and conducted using Taicang ATS and Dyna*CAS*. In this experiment, we increased the population size of the area from 31 to 41 thousand, and then have studied their effects on the traffic system. Take the average vehicle speed for example, as shown in Fig. 16; the average speed when crossing Intersection Feihu between 5:00 A.M. to 14:00 P.M. has dropped from 45 km/h to 30 km/h when the population is increased from 31 thousand to 35 thousand, and intersection congestion is a problem (see Fig. 16). As the population is increased to 41 thousand, the average speed drops to almost zero, leading to a state of total congestion. This indicates that when the population and activity growth in the selected area passes a certain threshold, we must improve the road infrastructure and take other measures to ensure healthy mobility in the area. Clearly, this study has demonstrated the effectiveness of PtMS in both managing the current traffic needs and evaluating, planning, and handling future traffic demands and requirements.

VI. CONCLUDING REMARKS

This paper summarized our research and development effort over the last decade in establishing a new mechanism for the parallel control and management of complex transportation systems. This control and management mechanism is the result of the integration and fusion of concepts and methods developed in AI, intelligent control, computational intelligence, intelligent systems, intelligent spaces, complex systems, complexity theory, social computing, CPSS, and advanced computational technologies, such as agent programming and cloud computing. We believe that it has opened a new field in a new direction that could significantly advance the effectiveness and intelligence level of intelligent transportation systems as well as promote their future applications.

However, more efforts are needed in both research and applications before concepts and methods in the ACP-based approach, in particular, the parallel system approach, including both parallel control and parallel management, can become well established, effective, and widely accepted in solving real-world complex problems. Clearly, the nature of many problems in transportation has made them ideal for testing, evaluating, and implementing those concepts and methods. The main purpose of this paper is to promote and call for more extensive discussion, investigation, and practices in this new and interdisciplinary direction within ITS communities.

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Fei-Yue Wang (S'87–M'89–SM'94–F'03) received the Ph.D. degree in computer and systems engineering from Rensselaer Polytechnic Institute, Troy, NY, in 1990.

He joined the University of Arizona, Tucson, in 1990 and became a Professor and the Director of the Robotics Laboratory and Program in Advanced Research for Complex Systems. In 1999, he founded the Intelligent Control and Systems Engineering Center at the Chinese Academy of Sciences (CAS), Beijing, China, under the support of the Outstanding Oversea Chinese Talents Program. Since 2002, he has been the Director of the Key Laboratory on Complex Systems and Intelligence Science, CAS. He is currently the Vice President of the Institute of Automation, CAS. From 1995 to 2000, he was the Editor-in-Chief of the *International Journal of Intelligent Control and Systems* and the *World Scientific Series in Intelligent Control and Intelligent Automation*. His research interests include social computing, web science, and intelligent control.

Dr. Wang is a member of Sigma Xi; an elected Fellow of the International Council on Systems Engineering, the International Federation of Automatic Control, the American Society of Mechanical Engineers, and the American Association for the Advancement of Science; an Association for Computing Machinery (ACM) Council Member at Large; and Vice President and Secretary-General of the Chinese Association of Automation. He has served as Chair of more than 20 IEEE, ACM, and Institute for Operations Research and the Management Sciences conferences. He was the President of the IEEE Intelligent Transportation Systems Society from 2005 to 2007; the Chinese Association for Science and Technology, USA, in 2005; and the American Zhu Kezhen Education Foundation from 2007 to 2008. He is currently the Editor-in-Chief of the *IEEE Intelligent Systems Magazine* and the IEEE Transactions on Intelligent Transportation Systems. He was the recipient of the National Prize in Natural Sciences of China in 2007 and the Outstanding Scientist Award by the ACM for his work in intelligent control and social computing.