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DynaCAS: Computational Experiments and Decision Support for ITS

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Accurate, reliable, and timely traffic information is critical for deployment and operation of intelligent transportation systems (ITSs). Traffic forecasting for travelers and traffic operators should become at least as useful and convenient as weather reports. In the US, the Federal Highway Administration (FHWA) has envisioned a real-time *traffic estimation and prediction system* (TrEPS) as an ITS support platform that resides at traffic management centers (TMCs) for dynamic route assignment (DRA) and other transportation operations.

To enable ITS deployment for urban traffic control and management in China, in 1999 the Chinese Academy of Sciences outlined a research agenda to develop related intelligent systems and technology.[1] A central component of this agenda was a TrEPS called DynaCAS (dynamic traffic assignment based on complex adaptive systems). Here, we briefly introduce DynaCAS and its open source counterpart DynaChina, emphasizing how they differ from other TrEPS projects.

Abbreviations

ADP: approximate dynamic programming
APTS: advanced public transportation system
ATIS: advanced traveler information system
ATMS: advanced traffic management system
CVO: commercial vehicle operation
DP: dynamic programming
DRA: dynamic route assignment
DTA: Dynamic Traffic Assignment
EMS: emergency management system
FHWA: US Federal Highway Administration
ITS: intelligent transportation system
TMC: traffic management center
TrEPS: traffic estimation and prediction system

Background

A deployable, real-time TrEPS is essential for many ITS subsystem applications, especially advanced traffic management systems (ATMSs), advanced traveler information systems (ATISs), advanced public transportation systems (APTSs), commercial vehicle operations (CVOs), and emergency management systems (EMSs).

A TrEPS provides traffic information to ITS subsystems to generate proactive, network-wide, coordinated guidance and control strategies. It also produces travel information for pretrip planning and route guidance to travelers for en route diversion. Its broad functional capabilities include[2]

- estimating and predicting short-term demands for traffic control and management;
- estimating and predicting traffic states;
- providing travel mode, departure time, route, and other information and advisories to travelers through ATISs to meet traffic management and control objectives; and
- interacting with other ITS subsystems or, in the interim, interfacing with ATISs and other ATMS support systems at TMCs.

In 1994, the FHWA initiated Dynamic Traffic Assignment (DTA), a long-term, multiphase research project to develop a deployable, real-time TrEPS. In 1995, the administration awarded two contracts to the Massachusetts Institute of Technology (MIT) and the University of Texas at Austin. Phase I DTA development was completed in October 1998, and two prototype TrEPSs were delivered for evaluation: DynaMIT,[3] developed at MIT, and DynaSMART,[4] developed at the University of Texas.

However, TrEPSs have seen limited application and success. Our goal is to learn from the DTA project and develop a deployable, real-time TrEPS that effectively supports ITS applications in China's urban transportation systems.

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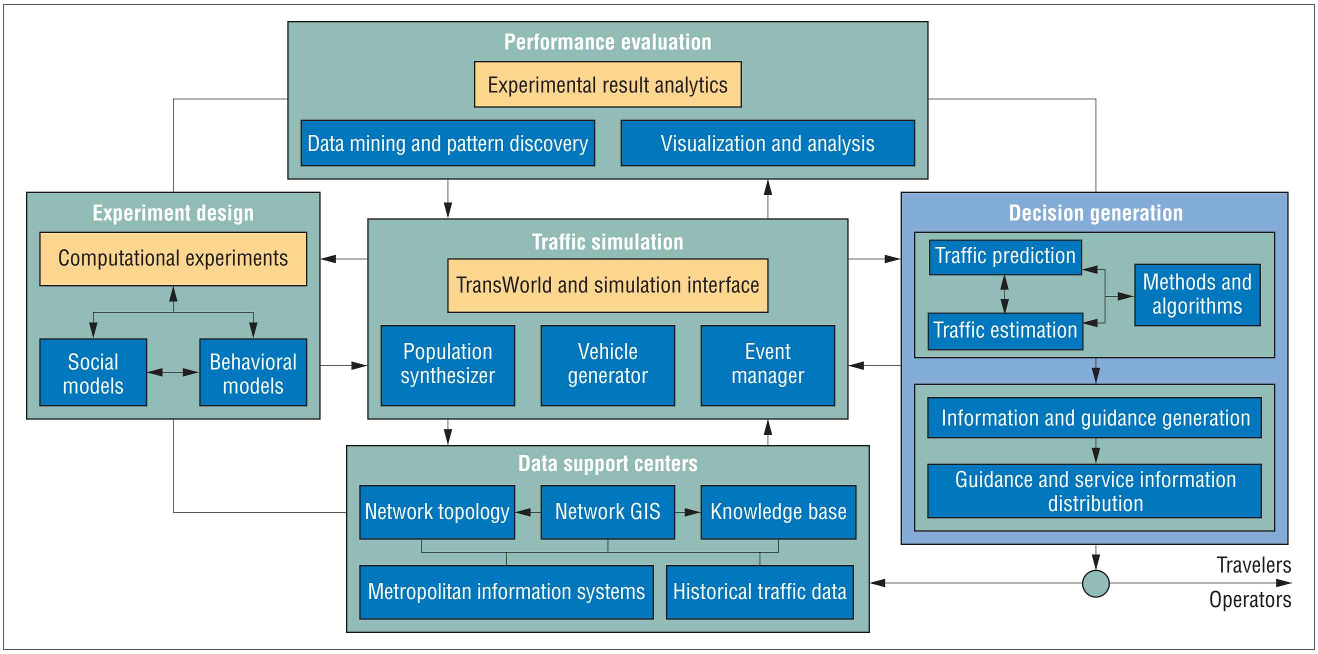

Figure 1. The DynaCAS framework. DynaCAS uses AI and complex-systems methods to provide additional flexibility and efficiency in traffic condition estimation and decision evaluation.

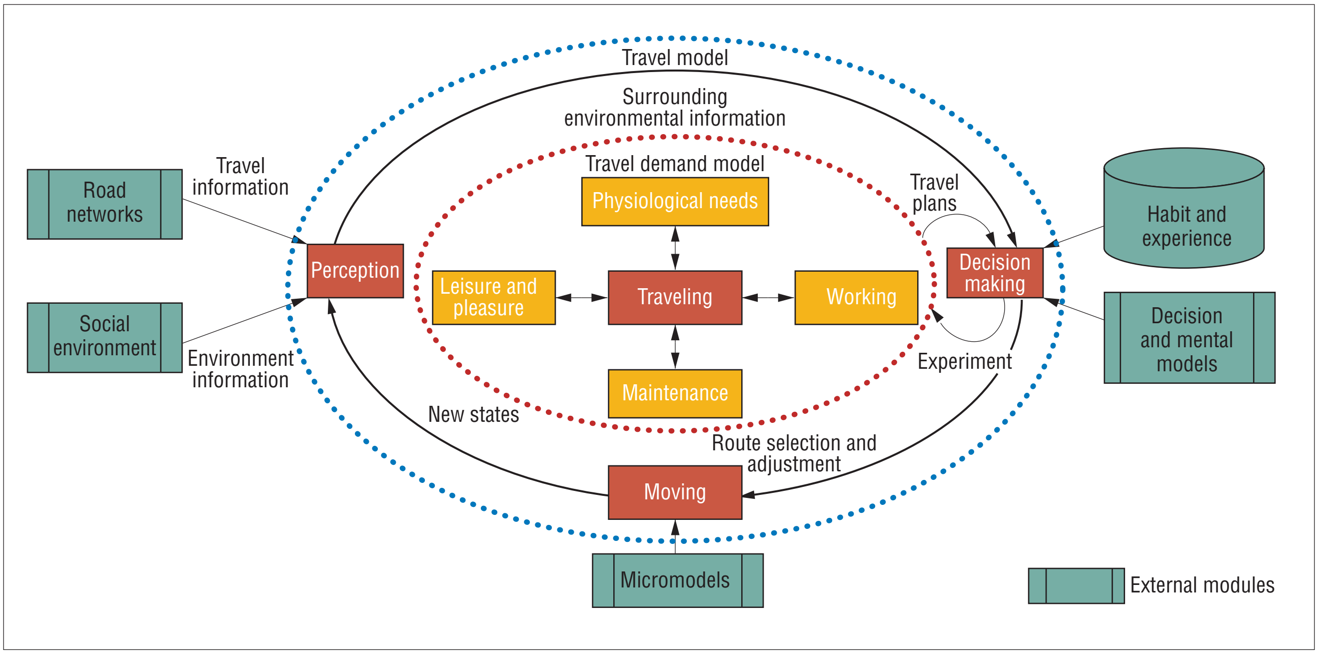

Figure 2. A model for individual behaviors in DynaCAS. This model links an individual's internal states with external information and events to generate traffic behaviors.

An Overview of DynaCAS

Figure 1 presents the DynaCAS framework. We pay special attention to rule-based computational modeling of social and behavioral aspects of people, vehicles, roads, and environments involved in transportation activities. We accomplish this through artificial-society methods and through emulations using the TransWorld modeling program. DynaCAS has five major building blocks: data support, experiment design, traffic simulation, decision generation, and performance evaluation.

DynaCAS represents transportation networks at four abstraction levels. In addition to the microscopic, mesoscopic, and macroscopic levels, we've introduced a logic representation to integrate social and economic, ecological and resource, construction infrastructure, logistical, and legal and regulatory factors. At the logic level, transportation modeling extensively employs qualitative information in linguistic forms. To achieve quantitative analysis, we use methods in computing with words and linguistic dynamic systems. We also use data-mining techniques to discover useful patterns from simulation results and computational experiments on all levels.

DynaCAS's main functionality includes

- estimation and prediction of traffic conditions,
- evaluation and optimization of traffic control and management decisions, and
- generation of route guidance for travelers and other information for traffic operators and service providers.

In addition to conventional TrEPS features, DynaCAS has these special features:

- fast estimation and prediction of traffic states using neural networks;
- design of traffic control algorithms through approximate dynamic programming (ADP);
- generation of traffic guidance and management information using the state classification method;
- microscopic modeling of individual travelers, vehicles, and roads;
- mesoscopic modeling of group behaviors and social events;
- macroscopic modeling of interactions among transportation and socioeconomic infrastructures; and
- computational experiments for road construction, special events, rare demands, severe weather, traffic incidents, and emergency management.

From Simulations to Computational Experiments

Simulations have provided a foundation for the development and deployment of DynaSMART, DynaMIT, and other TrEPSs. Computational experiments are a natural extension of computer simulations.[5] In applying computational experiments in DynaCAS, we use computers as alternatives to actual traffic systems, and TransWorld becomes a "living" traffic laboratory in which we systematically conduct simulations as "experiments." This is justified owing to the complexity of transportation problems and the corresponding subjectivity in their social and behavioral dimensions. This conceptual change toward simulations lets us use various methods and procedures developed in experiment design and social experiments for transportation studies, especially in dealing with problems with no analytic formulations.

In DynaCAS, we use computational experiments mainly to consider social and human factors and to perform these functions:

- *Problem identification*. We identify the problems or factors most critical to and influential on the specified transportation objective, especially when public opinion is involved. We can also conduct process and parameter identification for optimal and adaptive traffic decisions.
- *Procedure design*. We select the optimal procedure to combine different traffic solutions to solve complex traffic problems involving multiple stakeholders with conflicting interests.

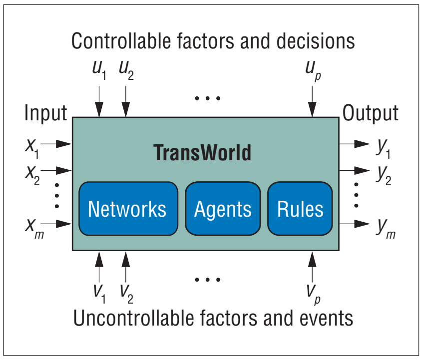

Figure 3. The general process of computational experiments. A computational experimental process aims to identify the controllable affecting factors and place them for desired purposes.

- *Performance evaluation*. We evaluate the effectiveness of different traffic decisions and the significance of various factors in a mixed social, economic, and engineering context.

To support those functions, we use both individual and group behavioral modeling to design computational experiments. Figure 2 shows a generic individual behavioral model, and Figure 3 presents the general process of computational experiments in DynaCAS. Specifically, through computational experiments, we want to determine

- which input factors most affect the outputs,
- how to place those inputs to produce outputs as close to the desired ranges as possible,
- how to place those inputs to make the variation in outputs as narrow as possible, and
- how to place those inputs to minimize the effect of uncontrollable factors.

These experiments must follow the three principles of experiment design: replication, randomization, and blocking.

For our computational experiments, we're also developing observation and explanation methods based on emergence theory. At this stage, we're considering only statistics, data-mining, pattern recognition, and other computational-intelligence algorithms for general situations. We plan to develop advanced procedures and algorithms for particular cases using application-specific AI techniques.

Approximate Dynamic Programming

In DynaCAS, planning is a short-term application, temporarily changing infrastructures, operational conditions, and so on. Travelers respond to the changes and in turn cause variations of traffic conditions. Scheduling periodically occurs to remove one or more lanes or set up an advance-warning area for a work zone. Hard control is signal control or ramp metering; soft control regulates traffic flow indirectly by a variable-message system, traffic news reports, a congestion information board, and so on, which travelers can ignore without breaking laws. Dynamic programming (DP) has been widely used for decision making in planning, scheduling, and soft and hard control.

In real-time traffic state estimation and route guidance, current solutions, especially those for DRA, fall into four groups: mathematical programming, variational inequality, optimal control, and simulation based. The first three are analytical and based on DP and other mathematical solutions such as dynamic user-optimal or dynamic system-optimal traffic assignment.

However, the inherently poor behavior of TrEPSs often causes problems with DRA algorithms' convergence and uniqueness, preventing their wide application. Furthermore, DP has limited application owing to its high computational and storage demands

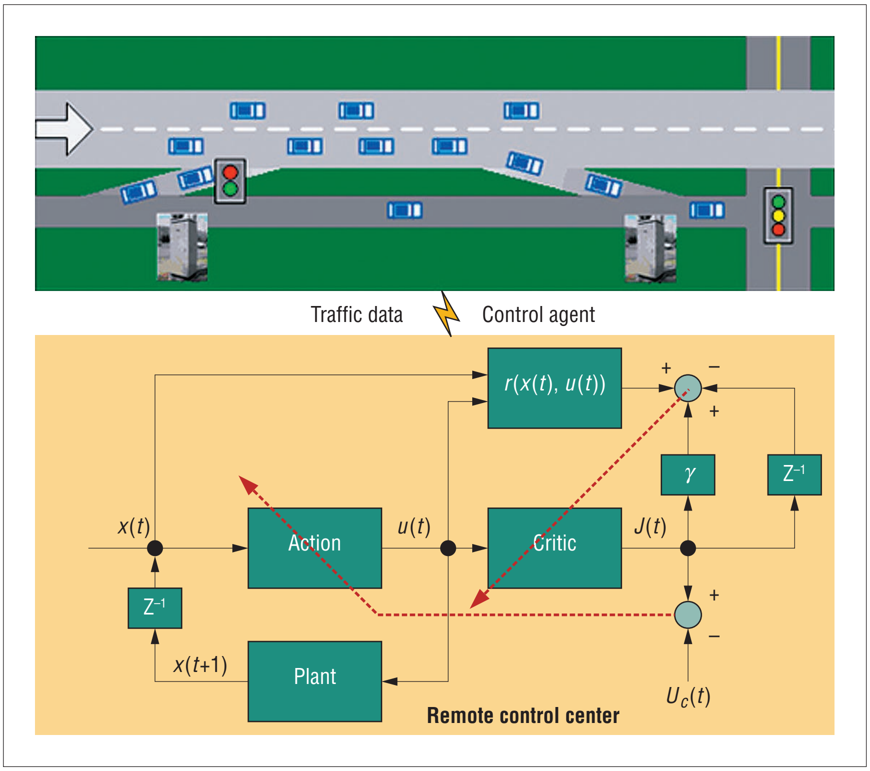

Figure 4. Approximate dynamic programming (ADP) for real-time and off-line traffic control. APD provides a unified approach for the design and implementation of traffic decisions in planning, scheduling, state estimation, route guidance, and soft and hard control.

for complex problems—the "curse of dimensionality."

Recently, researchers have proposed ADP to artfully circumvent such difficulties by using a critic network for estimating the performance function and its derivatives through dynamic programming and an action network to generate optimal actions.[6] Critic networks often use artificial neural networks for fast, effective approximation. In many cases, ADP combines backpropagation, reinforcement learning, and DP. DynaCAS has extensively applied ADP for traffic planning, scheduling, soft and hard control, and real-time state estimation and route guidance.

ADP-based approaches have many promising benefits, such as DP's optimality and feedback and neural networks' real-time performance. Another advantage is that these methods can handle systems with time-delay elements, an intrinsic property of traffic dynamics. Especially for traffic systems, supervised learning might not be a valid option because it utilizes instantaneous errors between the desired output and the actual output. However, ADPs are effective under such conditions because they let the neural network learn according to the present error state's cost-to-go function. This capability makes ADPs preferable for solving many traffic planning and control problems.[7]

Figure 4 shows a schematic for using ADP in traffic control. The action network can be any traffic controller, executing on freeway ramps or surface street intersections. The inputs to the action network are the system states $x(t)$, such as queue or travel time.

The action network outputs a control variable $u(t)$. The inputs to the critic network are $x(t)$ and $u(t)$. We use the critic network's output to estimate the discounted cost-to-go, $J(t)$. During the training process, we try to decrease the critic network's training errors to zero so that the critic network will accurately evaluate the action network's optimal traffic control performance. To achieve better convergence of the neural networks, we must carefully select $\gamma (0 < \gamma < 1)$, a discount factor for infinite-horizon problems, and $r(t)$, a reward or reinforcement signal for $u(t)$.

In some cases, the computational time required for ADP could be problematic, especially when we're using neural networks with many weight requirements for continual online adaptation. In addition, frequent online training could lead to instability. In those cases, we adopt the offline training mechanism to guarantee the convergence of the critic and the action networks.

For real-time implementation, we can deploy our ADP-based approach according to the local-simple and remote-complex design principle for networked systems.[8] For example, we conduct offline training at remote TMCs with actual traffic data. Once we've trained the complex neural-network-based traffic decisions, we convert them into simple, implementable formats and then download them to local sites in fields with fixed-weight parameters. This cycle can repeat hourly or daily until the parameters are tuned appropriately. Using this mechanism, we can avoid instability and guarantee real-time performance, reliability, and robustness in applications.

DynaChina

Along with DynCAS, the Chinese Academy of Sciences proposed DynaChina to organize and support transportation researchers in a joint effort for Chinese TrEPS development.[1] This is necessary because the development and deployment of TrEPSs is a long-term, multiphase project requiring wide and active participation by traffic researchers and practitioners. DynaChina aims to provide an open testbed to evaluate and verify DRA and other related traffic methods and algorithms. It also aims to establish a public platform to archive related R&D results and applications in a reusable, computationally executable fashion. A preliminary set of open architectures, standards, and application programming interfaces has been proposed for the construction of Web-based DynaChina.

With the recent, rapid development of Web computing, the Semantic Web, and Web science, DynaChina has become much more feasible and implementable. Obviously, similar open platforms can be established for other regional traffic systems and in different fields. Recognizing this possibility, a group of ITS researchers at the 2008 International IEEE Intelligent Transportation Systems Conference established a protocol for creating a searchable, computable ontology of transportation methods and algorithms. By the time you read this, researchers at the First Chinese Workshop on Artificial Transportation Systems will have investigated this topic further.

DynaCAS and DynaChina represent a major effort by Chinese ITS researchers to develop effective TrEPSs and apply DRA and related approaches to urban traffic network management. Besides methods and algorithms developed by transportation researchers, DynCAS extensively utilizes concepts and algorithms in AI and complex systems, especially computational experiments, rule-based fuzzy logic, neural networks, computing with words, linguistic dynamic systems, and ADP. Both theoretical studies and field tests have demonstrated that in many cases, those AI-based techniques are more flexible and effective than conventional analytic methods and are particularly useful for ill-formulated or heuristics-based traffic problems. Eventually, DynaCAS will likely incorporate additional AI and computational-intelligence methods, including data mining and machine learning.

Acknowledgments

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