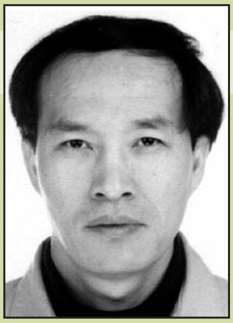


Editor: Fei-Yue Wang
University of Arizona and
Chinese Academy of Science
feiyue@sie.arizona.edu

RHODES to Intelligent Transportation Systems

Pitu Mirchandani, *University of Arizona*
Fei-Yue Wang, *University of Arizona and Chinese Academy of Science*

Ever since the major initiatives of the US, Europe, and Japan in the early 1990s to exploit communication, control, and computer advances to make transportation more efficient, reliable, and safe (as embodied in the US Intelligent Transportation System program), there have been implicit promises that the implementation will be soon. You only have to read the various articles on smart roads, smart vehicles, vehicle telematics, and so on to realize that the promises haven't yet been kept. For example, one promise was that, by now, most roads would include infrastructure allowing communication from a central system to most vehicles. In addition, most vehicles would be equipped so that through this communication drivers could obtain route guidance, warnings on lane departures, notification of vehicle malfunctions, and so on.

To be sure, researchers have conducted tests to show the feasibility of many of the promises, but full-scale deployment is still a ways away. Transportation agencies and automobile companies have realized that maybe they had promised too much and now have more modest goals and milestones. Even the US Federal Highway Administration's latest initiatives, such as the Intelligent Vehicle Initiative (www.its.dot.gov/ivi/ivi.htm) and Vehicle Infrastructure Integration initiative (www.its.dot.gov/initiatives/initiative9.htm), have modest goals for the next five to 10 years.

To help fulfill the promises of ITS, the ATLAS (Advanced Traffic and Logistics Algorithms and Systems—see the sidebar for more information) research center is developing and testing the RHODES (Real-Time Hierarchical Optimized Distributed Effective System) traffic control system.[1] We believe that RHODES will play a major role in the realization of future Advanced Traffic Management Systems, a major component of ITS.

Editor's Perspective

The IEEE Technical Activities Board has opened a new chapter in ITS-related R&D in the history of IEEE communities by elevating the ITS Council to an IEEE ITS Society. As the president-elect of the ITSS, I encourage you to participate in our activities through this department and the new society. While work to build the foundations of ITS technology has significantly accelerated over the last decade, many fundamental questions remain unanswered regarding ITS design, modeling, sensing, control, optimization, communication, architecture, implementation, performance, reliability, and so on. Nevertheless, there has been a proliferation of ITS methods, techniques, and commercial products, many of which have already been used successfully in real-world applications. This article summarizes recent R&D in Advanced Traffic Management Systems at the University of Arizona. *—Fei-Yue Wang*

The future of traffic management

It's envisioned that future ATMSs will know every vehicle's location (but not necessarily the identification of the vehicle or its driver, unless the driver has provided this information for extra services). Also, traffic management controls and advisories will ensure that vehicles in the network have the smoothest, safest, and most efficient ride from their origin to their destination.

The controls and advisories will include

- Traffic signals and the phase timings (A set of active signal lights—for example, north-south green with a red left-turn arrow and east-west red—is a *phase*; phase timing refers to the sequence of phases and each phase's time and duration.)
- Roadside or above-road changeable message signs
- Highway advisory radio
- Pretrip information through radio, television, and in-vehicle navigation systems
- Incident and road work information through radio and in-vehicle systems
- En route route guidance through in-vehicle systems

ATMSs will obtain traffic information from these sources:

- Inductive-loop detectors below the road surface

1541-1672/05/$20.00 © 2005 IEEE
Published by the IEEE Computer Society

ATLAS

The objectives of the Advanced Traffic and Logistics Algorithms and Systems research center are to

- Conduct basic research and system development on advanced technologies, information systems, and methods for traffic and logistics management
- Collaborate with agencies and industries and assist in the study and implementation of the state of the art in traffic and logistics management systems
- Enhance education and technology transfer activities that advance the state of the practice in traffic and logistics management

ATLAS collaborates with the US Federal Highway Administration, several state and local transportation agencies, other universities and research laboratories and institutes (including some in Europe, Asia, and South America), and many traffic and transportation companies in the private sector.

ATLAS has conducted research, development, and deployment in

- ATMS components, notably on RHODES, the MILOS (*M*ultiobjective *I*ntegrated *L*arge-Scale *O*ptimized Ramp-Metering Control *S*ystem) system for adaptive ramp metering, transit priority methods, wide-area traffic management, and real-time evacuation management
- Advanced Traveler Information Systems, including SPARTA (see the sidebar "The Living Laboratory") and the I-KIOSK for providing bus status and schedules
- Advanced public-transportation systems, including itinerary planning on the Web, online transit rescheduling, and integrating automatic vehicle location and traffic control for transit priority
- Intelligent-vehicles research, notably the VISTA (Vehicles with Intelligent Systems for Transport Automation) program, lane departure warning, and autopilots

ATLAS is also investigating new technologies and systems such as aerial data collection and monitoring and pedestrian recognition for traffic-adaptive signal control. In addition, the research center is developing new methodologies in traffic modeling, simulation, statistical evaluation, optimization, sensor location, and real-time algorithms.

- Video detectors over the roads that count vehicles in defined fields of view
- Other types of detectors such as microwave detectors, infrared detectors, acoustic detectors, and sonar detectors
- In-vehicle *automatic vehicle locators* that transmit the vehicle's location and other information (for example, some transit AVL systems provide location, passenger counts, and schedule adherence)
- Roadside vehicle identification sensors that read, for example, a permit allowing a vehicle's passage in a lane through toll payment or special permission (for example, HOT lanes on some highways allow a high-occupancy [HO] vehicle free passage while charging a toll [T] for single or low-occupancy vehicles)
- Drivers who voluntarily provide information to obtain a service (for example, route guidance)

RHODES doesn't yet employ all these controls, advisories, and information sources. However, its modular architecture will let us build on the communication-control-computer infrastructure to provide additional functions for ITS.

The RHODES system

RHODES takes as input sensor data from detectors, AVLs, transponders, and so on. It produces real-time predictions of traffic flow and "optimally" controls the flow through the transportation network, using phase timing.

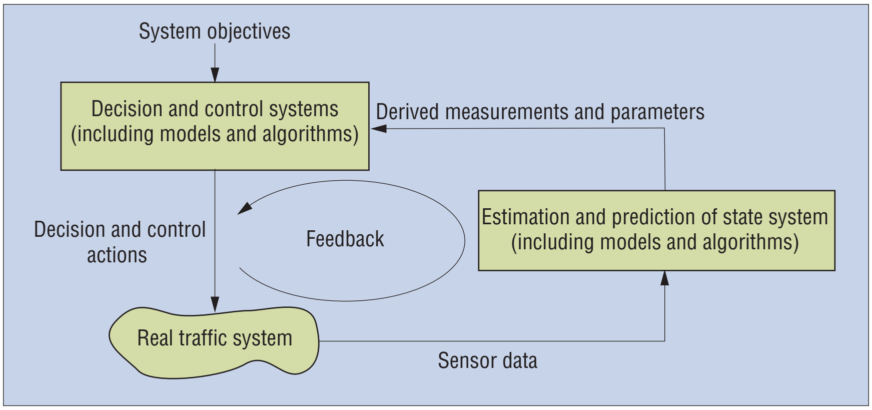


Figure 1. A feedback control diagram for traffic-adaptive systems.

Traffic-adaptive signal control

Vehicle arrival at a traffic signal is stochastic; vehicles arrive sometimes singly and sometimes in batches or *platoons*. Interarrival times (times between vehicles or platoons) vary nondeterministically, being affected by time-of-day traffic conditions, the vehicle mix, upstream incidents and bottlenecks, the mix of driver types (defined by purpose, socioeconomic and demographic variables, and driver personality), and the physical layout of the road and lanes. To be effective, real-time traffic-adaptive signal control must proactively respond to the arrival streams to minimize vehicle stops and delays as much as possible.

The feedback control diagram in Figure 1 illustrates an effective traffic-adaptive signal control system. The sensors monitor the traffic on the network. Using a traffic model, the system estimates the current traffic flow and predicts future traffic flow. Using an optimization algorithm or an optimum-seeking heuristic, it then determines the best plan or phase timing to apply for the next control period. The traffic-adaptive systems being implemented in the US, Europe, Australia, and a few Asian countries differ in

- What they assume about traffic flow patterns
- How they estimate traffic flow

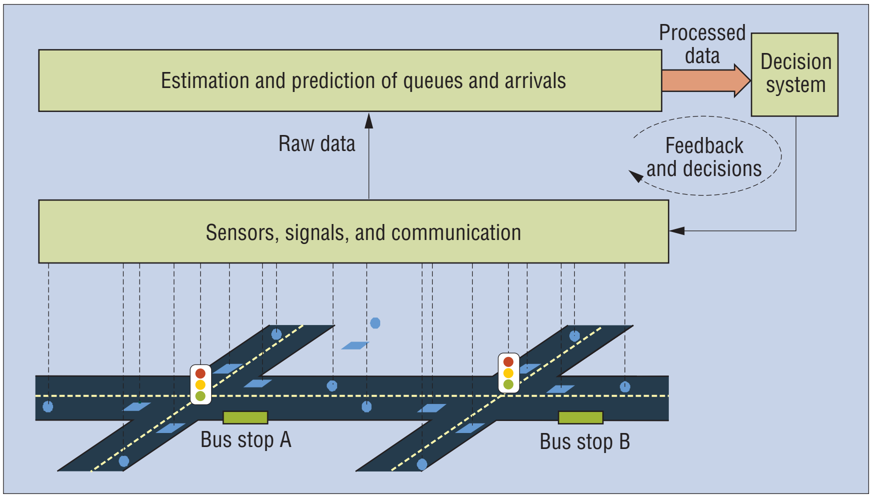


Figure 2. A simplified diagram of RHODES operation.

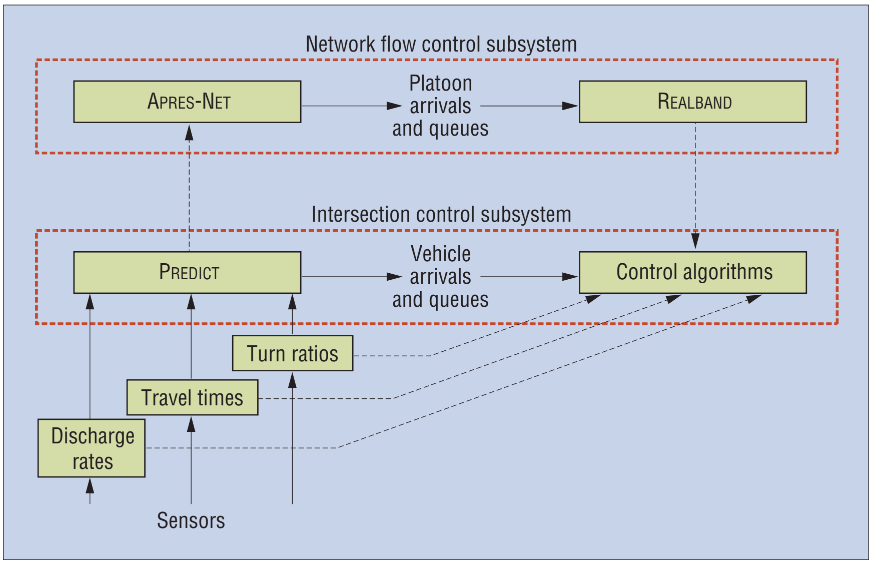


Figure 3. The middle and lower levels of the RHODES hierarchical control architecture.

- How they optimize signal phasing

RHODES employs a traffic-adaptive signal control architecture that

- Decomposes the traffic control problem into subproblems that are interconnected hierarchically.
- Predicts traffic flow at appropriate resolution levels (individual vehicles, platoons, transit vehicles, emergency response units, and trains) to enable proactive control.
- Supports various optimization modules for solving the subproblems.
- Employs data structure and computation and communication approaches that allow fast solution of the subproblems.

This lets RHODES implement each decision within an appropriate rolling time horizon of the corresponding subproblem.

As the main optimization approach, RHODES uses *dynamic programming* (DP). The performance criterion for the DP can be any provided by the authority responsible for the system, as long as it's based on traffic measures of effectiveness (such as average delays, stops, and throughput).

How RHODES operates

Figure 2 depicts a simplified operational diagram for RHODES. Basically, the system carries out two main processes. The first is *estimation and prediction*, which takes the sensor data and estimates the actual flow profiles in the network and the flows' subsequent propagation. The second process involves the *decision system*, which selects the phase timing to optimize a given objective function, the optimization being based on DP and decision trees. Possible objectives include minimizing the average delay per vehicle, minimizing the average queues at intersections, and minimizing the number of stops. When the objective function considers delays, the computation of the objective function's value might involve assigning a weight to each vehicle to reflect its delay. This weight increases when the vehicle waits too long in a queue.

The decision system has a hierarchical control structure. At the highest level is a *dynamic network loading* (DNL) model that captures traffic characteristics that vary slowly over time. These characteristics pertain to the network geometry (available routes including road closures, construction, and so on), travel demand (roughly, the number of people wanting to go from their origin to their destination), and the travelers' typical route selection (for example, choosing routes such that travel times on a selected set of routes from an origin to a destination are nearly equal). On the basis of these characteristics, the system can estimate the load on each particular road segment, in terms of vehicles per hour. These estimates provide RHODES with prior allocations of *green times* (times when the traffic signals are green) for each different demand pattern and each phase (north-south through-movement, north-south left turn, east-west left turn, and so on).

At the middle level, called *network flow control*, the system updates the green-time decisions. At this level, the system measures traffic flow characteristics in terms of platoons of vehicles and their speeds.

Given the approximate green times, the *intersection control* at the lowest level selects the appropriate times for phase changes. It does this on the basis of observed and predicted arrivals of individual vehicles at each intersection.

Figure 3 depicts the control structure for the middle and lower levels. Essentially, each of these levels contains an estimation module and a control module. APRES-NET and PREDICT are estimation modules, and REALBAND is a control module. The control algorithms at the intersection control level are the DP optimization models, such as the CAPRI (Categorized Arrivals Based

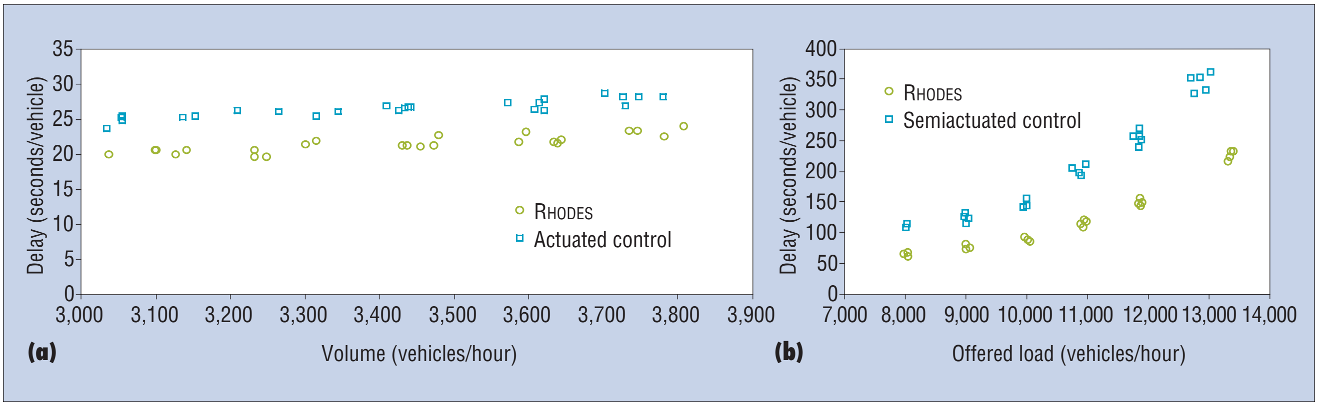


Figure 4. Average vehicle delays versus throughput (vehicle trips per hour): comparing RHODES with (a) actuated control at an interchange and (b) semiactuated control for a major surface street segment.

Phase Reoptimization at Intersections) strategy.[2–6]

RHODES and ATMS

Each level of RHODES control has potential useful applications in ATMS.

Dynamic network loading

The DNL module hasn't been fully developed or field tested. However, we've simulated tests of the preliminary models. Once operational, this module will take as input all the transportation planning data (obtainable from planning agencies), such as daily trips by mode, time of day, and day of week, from origins to destinations. It will fuse this data with real-time sensor data to estimate current traffic patterns. Besides predictions for lower-level control in RHODES, this module will provide

- Pretrip and in-vehicle route guidance
- Route advisories for specialized vehicles such as emergency responders (fire department, police, and ambulances) and vehicles carrying hazardous materials
- Time-dependent traffic data for better design of transportation networks

One application of DNL that ATLAS is studying is real-time traffic management for emergency evacuation. Given real-time traffic information and estimates of the population distribution at the time of the emergency incident (which are available from planners), this application provides a regional perspective to guide vehicles, in real time, from the incident location to safe destinations.[7]

Network flow control

Effectively, the network control level tries to open *green bands* for the defined platoons. (In a green band, traffic signals at a set of consecutive intersections are timed to be green so that vehicles in the platoon don't have to stop at the intersections.) But two other "clients" of ATMSs require special considerations when using a signalized network: emergency vehicles and trains.

An emergency vehicle, such as a fire truck that requires fast, safe passage from its station to the emergency site, can be considered a platoon of one that requires a green band. The RHODES architecture allows signal optimization so that the emergency vehicle gets the green light while the rest of the traffic faces minimal delays.

Trains, on the other hand, already have a preemption authority that makes their signal green regardless of the network traffic when road-level railroad crossings exist. If RHODES can obtain advance information on the train's movement through crossings, it can provide green lights for the affected vehicles so that they're moved out of the crossing zones and delayed less. In addition, if changeable-message signs are near railroad crossings, ATMSs can provide drivers information on alternative routes in conjunction with the optimized phase timings that RHODES provides.[3]

Intersection control

Other ATMS clients are buses and other transit vehicles. When a bus is running late, it would be appropriate to give it some priority through signalized intersections to decrease its delay while not greatly increasing other drivers' delays. The DP optimization model lets RHODES give a higher weight to a delayed bus (that is, much higher than that for a private automobile). This weight appropriately takes into account trade-offs between bus delays and other vehicle delays in setting phase durations. Simulation-based experiments show that we can significantly reduce bus delays with little effect on traffic delays on the cross streets (the traffic delay in the bus's direction generally decreases). We're also planning to field-test how well RHODES performs with this transit priority.[8]

If sensors can be designed that detect pedestrians and bicycles—also ATMS clients—the intersection control module will also be able to consider trade-offs among delays of pedestrians, bicycles, cars, and buses. ATLAS is developing video-based pedestrian detectors and is planning to field-test a RHODES version that considers both pedestrian and vehicular demands.

Testing RHODES

Figure 4a shows typical simulation results. The figure is from an analysis using a simulation model of a diamond interchange in Tempe, Arizona. (A diamond interchange is an interchange between a freeway and a surface street that looks like a diamond.) It indicates that RHODES could decrease vehicle delays compared to well-timed actuated control for the same interchange. (Actuated control slightly increases or decreases a phase duration on the basis of some logical function of the actuations of the loops just upstream of the intersection.)

Figure 4b compares RHODES with semiactuated control (also called actuated coordinated control) for a major surface street segment with eight intersections at Tara Boulevard in Atlanta. RHODES performs much better than semiactuated control; average vehicle delays decrease from 50 percent (for low loads) to 30 percent (for

The Living Laboratory

An important component of Atlas (see the other sidebar) is the Living Laboratory for Transportation Technologies, which lets researchers pretest and post-evaluate technologies and systems. Besides typical traffic equipment such as traffic controllers, traffic signal cabinets, and computers, it includes high-speed network connections via optical fiber to the Traffic Operations Center in Tucson, Arizona. This lets researchers access near-real-time status information for over 350 intersections in the Tucson metropolitan region. A similar connection with the city's public-transportation operations provides Atlas real-time status and position information of all transit fleet vehicles. A network of 15 intersections near the University of Arizona has also been instrumented to provide real-time status information, such as second-by-second detector and signal status, which is available for research and monitoring. Figure A indicates the intersections that constitute this network, which are being monitored and tested with the Rhodes traffic control system. (For more on Rhodes, see the main article.)

This network connectivity has let the laboratory design Sparta (System for the Prediction and Analysis of Real-Time Traffic on Arterials), a Web-based traffic information system. Each second, Sparta updates its database with each intersection's signal status, active timing plan, vehicle detector and pedestrian actuations (which occur when a vehicle goes over an induction-loop detector or a pedestrian presses a crosswalk button), and peer communications status, providing a rich source of data. With appropriate login permissions, researchers can retrieve this second-by-second information for any time period. Sparta also lets researchers obtain derived measures, such as occupancy, lane utilization, volume counts (per lane), phase utilization, phase splits (the distribution of green times for a phase), and cycle lengths. (A *phase* is a set of active signal lights—for example, north-south green with a red left-turn arrow and east-west red.) Using Rhodes controller information, we can also obtain estimated queue lengths and are working to obtain estimates of travel times for road segments, turn proportions (the percentage of traffic that goes straight, turns right, and turns left), and queue discharge rates.

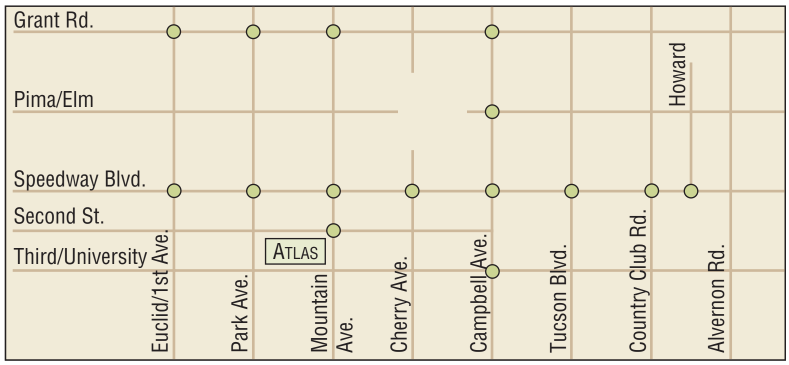


Figure A. The Living Laboratory for Transportation Technologies includes a section of the transportation network near the University of Arizona that has been instrumented for testing the Rhodes traffic control system. Circles indicate Rhodes-controlled intersections.

high loads). In the high-load case, not only are the average delays smaller but also the delay's variance is significantly reduced, making movement through the network more predictable for the driver.

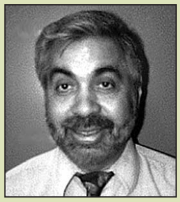
We conducted the first Rhodes field test in Tempe, Arizona, in September 2000.[9] Subsequently, we tested it in Seattle in summer 2002; in Tucson, Arizona, in winter 2002; in Oakville, Canada, in summer 2004; and in Santa Clara, California, in fall 2004. In most of the tests, Rhodes improved traffic performance; it didn't hurt performance in any test (that is, it at least matched a well-timed system). We plan more tests, with further enhancement of Rhodes, in Pinellas County, Florida, in Seattle, and in Houston, Texas. The Chinese Academy of Sciences in Beijing is also using Rhodes to develop the GreenPass traffic control and management system for the 2008 Olympics.[10] GreenPass is undergoing field testing in Shandong, China. In addition, Atlas is using Rhodes in conjunction with its Living Laboratory for Transportation Technologies (see the sidebar "The Living Laboratory").

Rhodes can provide a strategic road toward realizing the promise of ITS's advanced-traffic-management functions. Preliminary simulation analyses and field testing have planted seeds that might eventually produce fruit that will benefit travelers on our congested highways and streets. Of course, full realization of Rhodes's potential will require the confidence and the cooperation of traffic agencies, and national organizations such as the Federal Highway Administration will need to convince local agencies that ITS and ATMS can benefit all citizens. ■

Acknowledgments

The Federal Highway Administration, the National Science Foundation (Grant CMS-0231458), the Arizona Department of Transportation, and the cities of Tucson and Tempe have supported this research. This article's contents reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents don't necessarily reflect the official views of this research's sponsors. We especially acknowledge Larry Head and David Lucas of Atlas for their contributions to Rhodes. We also thank others who have worked on devel-

oping RHODES: research colleagues Suvrajeet Sen (Univ. of Arizona) and Paolo Dell'Olmo (Univ. of Rome, La Sapienza); former students Steve Shelby and Douglas Gettman; and Douglas Crawford (Siemens Intelligent Transportation Systems), Raj Ghaman (Federal Highway Administration), Jim Decker (City of Tempe), Tim Wolfe (Arizona Dept. of Transportation), and Sarath Joshua (Maricopa Assoc. of Governments), who all collaborated on the field tests.



Pitu Mirchandani is the Salt River Project Professor of Technology, Public Policy, and Markets at the University of Arizona and has joint appointments in the university's Systems & Industrial Engineering Department and Electrical & Computer Engineering Department. He's also the director of the ATLAS (Advanced Traffic and Logistics Algorithms and Systems) Center at the university. Contact him at the ATLAS Center, Old Engineering Bldg. 20, Univ. of Arizona, Tucson, AZ 85721; pitu@sie.arizona.edu.

Fei-Yue Wang is a professor in the University of Arizona's Systems & Industrial Engineering Department and the director of the University's Program for Advanced Research for Complex Systems. He is also the director of the Intelligent Control and Systems Engineering Center at the Chinese Academy of Sciences' Institute of Automation. Contact him at the Systems & Industrial Eng. Dept., Univ. of Arizona, Tucson, AZ 85721; feiyue@sie.arizona.edu.

References

1. P.B. Mirchandani and K.L. Head, "A Real-Time Traffic Signal Control System: Architecture, Algorithms, and Analysis," *Transportation Research Part C*, vol. 9, no. 6, 2001, pp. 415–432.
2. S. Sen and K.L. Head, "Controlled Optimization of Phases at an Intersection," *Transportation Science*, vol. 31, no. 1, 1997, pp. 5–17.
3. P.B. Mirchandani and D.E. Lucas, "Integrated Transit Priority and Rail/Emergency Preemption in Real-Time Traffic Adaptive Signal Control," *J. Intelligent Transportation Systems*, vol. 8, no. 2, 2004, pp. 101–115.
4. P. Dell'Olmo and P.B. Mirchandani, "REALBAND: An Approach for Real-Time Coordination of Traffic Flows on a Network," *Transportation Research Record*, no. 1,494, 1995, pp. 106–116.
5. P. Dell'Olmo and P.B. Mirchandani, "A Model for Real-Time Traffic Coordination Using Simulation-Based Optimization," *Advanced Methods in Transportation Analysis*, L. Bianco and P. Toth, eds., Springer-Verlag, 1996, pp. 525–546.
6. K.L. Head, "An Event-Based Short-Term Traffic Flow Prediction Model," *Transportation Research Record*, no. 1,510, 1995, pp. 45–52.
7. P.K.G.R. Rao, *Dynamic Traffic Management Methodology for Flooding Evacuation*, MS thesis, Systems and Industrial Eng. Laboratory, Univ. of Arizona, Tucson, Dec. 2004.
8. P.B. Mirchandani et al., "An Approach towards the Integration of Bus Priority, Traffic Adaptive Signal Control, and Bus Information/Scheduling Systems," *Computer-Aided Scheduling of Public Transport*, S. Vos and J. Daduna, eds., Springer-Verlag, 2001, pp. 319–334.
9. P.B. Mirchandani and D.E. Lucas, *Implementation and Field Testing of RHODES, A Real-Time Traffic Adaptive Control System*, Final Report FHWA-AZ01-447, Ariz. Dept. of Transportation, 2001.
10. F.-Y. Wang et al., "Toward Intelligent Transportation Systems for the 2008 Olympics," *IEEE Intelligent Systems*, vol. 18, no. 6, 2003, pp. 8–11.

For more information on this or any other computing topic, please visit our Digital Library at www.computer.org/publications/dlib.