The Exploratory Advanced Research Program

EXPLORATORY ADVANCED RESEARCH

Next Generation Traffic Control Systems

WORKSHOP SUMMARY REPORT • FEBRUARY 3–4, 2015

U.S. Department of Transportation
Federal Highway Administration

Foreword

The Federal Highway Administration's (FHWA's) Exploratory Advanced Research (EAR) Program addresses the need to conduct longer term and higher risk breakthrough research with the potential for transformational improvements to plan, build, renew, and operate safe, congestion free, and environmentally sound transportation systems. The EAR Program can accelerate and advance innovative methods by changing the mechanisms used to conduct research and the group of people who have access to research tools by leveraging new information science and communications technologies.

On February 3–4, 2015, at the Turner–Fairbank Highway Research Center in McLean, VA, the FHWA's Office of Operations Research and Development, with support from the EAR Program, convened the 2-day workshop, "Next Generation Traffic Control Systems." The workshop brought together researchers and technology developers from industry, academia, and public agencies to discuss the direction of technological advances in traffic control systems and sensors. The workshop participants identified research gaps, barriers, and needs that could be addressed to improve the utility of sensors for traffic management. Participants also discussed how to accelerate the development of tools for future signal control research, the need for these tools, the potential benefits, and future considerations for their development and dissemination.

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Notice

Quality Assurance Statement

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16. Abstract On February 3–4, 2015, at the Turner–Fairbank Highway Research Center in McLean, VA, the Federal Highway Administration's Office of Operations Research and Development, with support from the Exploratory Advanced Research Program, convened the 2-day workshop "Next Generation Traffic Control Systems." The purpose of this workshop was to bring together researchers and technology developers from industry, academia, and public agencies to discuss the direction of technological advances in traffic control systems and sensors.			
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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List of Acronyms and Abbreviations

CDF	cumulative distribution function
DOT	department of transportation
EAR	Exploratory Advanced Research
FHWA	Federal Highway Administration
GID	geographic intersection design
GPS	global positioning system
ITS	intelligent transportation system
JPO	Joint Program Office
MAC	machine access code
MIDAS	managing interactive demands and supplies
MOEs	measures of effectiveness
R&D	research and development
RHODES	real-time hierarchical optimized distributed effective system
RSE	roadside equipment
SPaT	signal phase and timing
USDOT	U.S. Department of Transportation
V2I	vehicle to infrastructure
V2V	vehicle to vehicle

Introduction

On February 3–4, 2015, at the Turner–Fairbank Highway Research Center in McLean, VA, the Federal Highway Administration's (FHWA's) Office of Operations Research and Development (R&D), with support from the Exploratory Advanced Research (EAR) Program, convened a workshop on "Next Generation Traffic Control Systems." The purpose of this 2-day workshop was to bring together researchers and technology developers from industry, academia, and public agencies to discuss the direction of technological advances in traffic control systems and sensors. Workshop participants discussed a different set of issues on each day of the workshop. On the first day, the participants primarily focused on the promise of advances in infrastructure-based and mobile-sensor technology to offer new and substantial capabilities in measuring traffic speeds, volumes, origin–destination pairs, and other data that enable improved traffic control. The participants identified research gaps, barriers, and needs that could be addressed to improve the utility of sensors for traffic management, particularly to enable the next generation of adaptive signal control. On the second day, workshop participants focused on the importance of researching and developing new traffic-signal control algorithms and the complex simulation infrastructure that it requires. The participants discussed how to accelerate the development of tools for future signal control research, the need for these tools, the potential benefits, and future considerations for their development and dissemination.

DAY 1:
NEXT-GENERATION SENSORS

Opening Remarks

Advances in infrastructure-based and mobile-sensor technology promise to offer new and substantial capabilities in measuring traffic speeds, volumes, origin–destination pairs, and other data that enable improved traffic control. This first day of the workshop involved identifying research gaps, barriers, and needs that could be addressed to improve the utility of sensors for traffic management, particularly to enable the next generation of adaptive signal control.

Dr. Joseph Peters and David Gibson of FHWA provided an overview of traffic control system and sensor technology and how they relate to their work, after which they described the mission of the Office of Operations R&D and its goal to advance state-of-the-art transportation operations. They described how the specific objectives of the office are to (1) drive technology work and evaluation of concepts; (2) engage state-of-the-art professionals from industry and Ph.D. students from academia; (3) support professional development to provide the value necessary for investment; and (4) support the mission of FHWA.

David Kuehn, EAR Program Manager, then discussed the purpose of the EAR Program. Kuehn stated that the EAR Program works to understand the various roles of technology and connectivity for the future. Kuehn noted that a vision of a connected and automated future is a big part of this role and communication between vehicles and infrastructure is required to take full advantage of the technology and reduce congestion. Kuehn highlighted speed harmonization as one example of a way that traffic can be controlled through connectivity to improve mobility.

Gibson explained that the motivation for this workshop is the need to move beyond contact-closure sensors (i.e., devices that detect the open or closed status of a circuit) toward those that can support vehicle identification, re-identification, and location. Traffic control systems with these types of sensors could transform how optimization algorithms work and provide new types of data and information. Research on how to develop these sensors must answer the following questions:

- What are the benefits of increased data fusion and spectral imaging at new wavelengths?
- What are the benefits of looking at data fusion with information obtained outside of vehicle sensing?

Next, expert speakers from industry and academia presented their research to the workshop participants. These presentations are summarized in the following section.

How Can Advances in Science and Technology Enhance or Supplant Current Sensors or Control Systems?

Dr. Jakob Eriksson
Assistant Professor, University of Illinois, Chicago

Overview
Dr. Eriksson began his presentation with some background information on traffic sensors and introduced three categories of sensors: passive, semi-passive, and active. He then described the developments that need to occur within the sensor technology field to provide improved accuracy and more comprehensive data. Dr. Eriksson highlighted that his presentation was intended to spark a discussion about the future of traffic sensing technologies.

Major Themes Discussed
During his presentation, Dr. Eriksson discussed a range of traffic sensors. These are summarized as follows:

Passive Sensors
Dr. Eriksson explained that passive sensors require no participation from the driver and may include inductive-loop detectors, radar, camera or computer vision, and license-plate readers. He noted that computer vision holds many promising uses for the future, including continuous turn counts and the ability to sense from arbitrary perspectives, that could overcome today's limitations caused by heavy occlusion.

Semi-Passive Sensors
Dr. Eriksson described how semi-passive sensors require participation from drivers' devices without their knowledge and can include applications such as roadside Bluetooth®, Wi-Fi, tire-pressure sensor sniffers, radio-frequency identification, cellular hand-off signals, and applications on smart phones. figure 1 illustrates how reidentifying wireless sniffers can be positioned to overhear and record unique addresses contained within transmissions from these devices. This could include the transmission of a unique address from Bluetooth or tire-pressure sensors. Dr. Eriksson stated that cellular hand-off signals are useful because they produce a lot of data; however, service providers might restrict access to the reidentification or tracking information and granularity is coarse (i.e., less detailed) and inconsistent across providers. He also noted that some of these uses have privacy issues, especially those associated with smartphone applications that report global positioning system (GPS) coordinates.

Active Sensors
Dr. Eriksson noted that active sensors require that a driver participate knowingly and have a personal interest in providing data. He provided some example applications for these sensors, including fleet-tracking networks and mobile applications that allow users to report scenarios such as accidents and construction. Dr. Eriksson mentioned that there may be some legal concerns associated with these applications; however, creating an incentive for the user to provide data could prove to be useful. He suggested engaging the driver directly

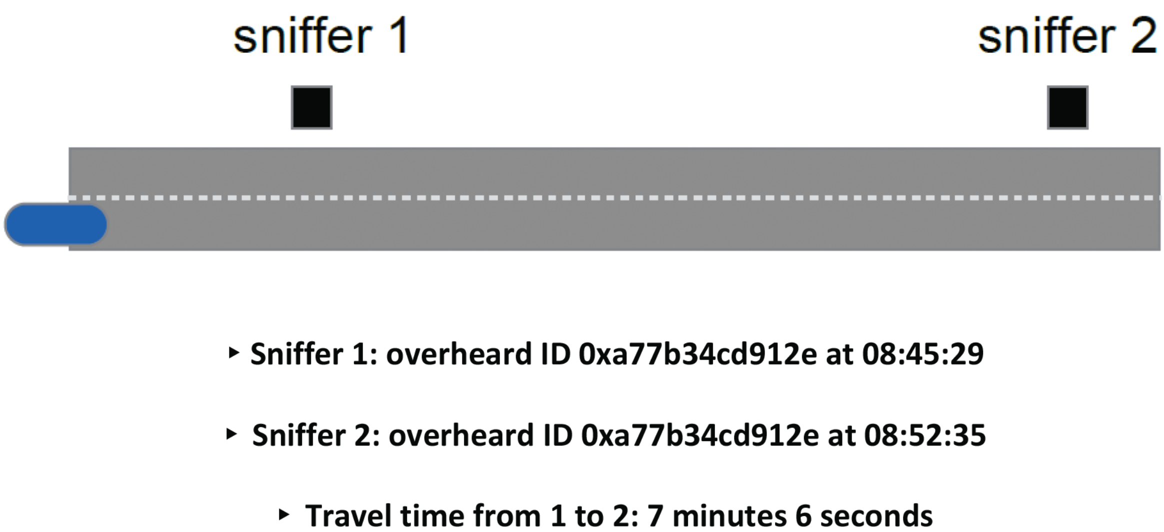

Figure 1. Roadside layout of reidentifying wireless sniffers.

to establish a customer relationship, which can then be used to incentivize changes in driving patterns. Dr. Eriksson noted that a "frequent-driver" program such as this would create a large amount of data that could prove useful for many purposes. He also suggested that willing participants often lead to more accurate and reliable data.

Next Generation Sensors

Dr. Eriksson suggested that any next generation sensing technology must be statistics-based and actionable in real time. He explained that statistics-based sensors are those that can estimate congestion state; hourly-turn probabilities; and current traffic volume, speed, and vehicle mix. Real-time actionable sensors are those that are useful and can detect the presence of vehicles and pedestrians. These sensors are able to count vehicles, predict vehicle-arrival times, and detect vehicles that are obstructing upstream or downstream intersections.

In summary, Dr. Eriksson highlighted the importance of using several different types of sensors together in the system, known as sensor fusion. He also suggested that combining passive, real-time, and active sensors with "frequent-driver" programs could provide more comprehensive and accurate data.

Advances in Infrastructure-Based Sensors

Dr. Lianyu Chu
President, CLR Analytics Inc

Dr. Henry Liu
Professor, University of Michigan Transportation Research Institute

MODERATOR
Raj Ghaman
Texas Transportation Institute

Improving Loop-Detectors

Dr. Chu presented his research on loop detectors and made some recommendations for their improvement. Dr. Chu explained that the basic function of a conventional loop detector is to obtain volume, speed, and lane occupancy data. He suggested that advanced loop detectors could obtain this basic information in addition to a unique vehicle signature to classify each vehicle.

Vehicle Signatures

Dr. Chu described how a signature can be determined from a vehicle's size, number of axles, metal mass, and height of undercarriage. Dr. Chu noted that different types of vehicles have different vehicle signatures and the signatures from vehicles of the same vehicle class show some similarities. He mentioned that researchers are currently developing and testing detectors that can read these vehicle signatures. Detectors can produce very similar vehicle signature readings for the same vehicle with different detector loop shapes at different locations (e.g., a circle loop on the upstream traffic and a square loop on the downstream traffic). Dr. Chu highlighted that the two core algorithms that can use the signature data are vehicle reidentification and vehicle classification. Based on a dataset collected in California, he noted that the rate of accuracy for vehicle matching is 66.8 percent, which can be used to derive more reliable and accurate travel times. He stated that the vehicle classification accuracy within the FHWA vehicle classification scheme is 92.4 percent.

Future Applications

Dr. Chu suggested that a new signature-capable detector card is needed to advance this sensing technology. Figure 2 shows a traffic controller cabinet used to field test a signature-capable detector card. Dr. Chu mentioned that development is underway and includes field tests in California and Minnesota. He suggested that these detector cards will be useful for both freeways and arterials, and they will work with existing traffic controller cabinets compatible with both 170/2070 and National Electrical Manufacturers Association standards. Dr. Chu suggested some potential applications could include: high-definition traffic system performance monitoring, conversion of vehicle-detection stations to vehicle-classification stations, estimating emissions, collecting origin–destination data, counting intersection turns, tracking heavy vehicles, and detecting bicycles.

Improving Data Quality

Dr. Liu presented his research on infrastructure-based traffic control system data and next generation traffic control systems. He explained that the current generation of intelligent traffic-signal systems uses fixed-location sensors to produce performance measures. These performance measures

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Figure 2. A traffic controller cabinet used to field test a signature-capable detector card.

are used to create signal-control algorithms, which feed traffic-signal devices. Dr. Liu noted that most systems are closed-loop systems, and bicycles and pedestrians are often passive parts of the systems. He highlighted that these types of systems do not produce good data but vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication can improve the data collected from traffic signals. Dr. Liu explained that his research team developed a data-collection device to improve the quality of the data collected from traffic signals.

Data Collection

Dr. Liu noted that field tests of TS-1 signal-control cabinets, which exist in many locations but are no longer the current standard, show that they can collect and archive every vehicle actuation and signal change before sending this information to a traffic control center.[1] Dr. Liu highlighted that each vehicle produces two data points: actuation and de-actuation. These data can help with the measurement of performance at the intersection level. For example, he stated that they could help with the estimation of queue length and travel time, as well as identify oversaturated conditions. Dr. Liu mentioned that with queue-length data it is possible to derive other measures, including delay, level of service, and number of stops. Moreover, he noted that looking at several intersections in a row will allow for the analysis of corridor-level travel time, trip delay, number of stops, and emissions. Dr. Liu suggested that once the performance measures are derived, it is possible to identify if there are any problems with a traffic signal.

Future Testing

Dr. Liu mentioned that next generation intelligent traffic-signal systems will enable controllers to advise individual vehicles on speed and route options. He noted that in these systems, vehicles, pedestrians, and bicycles are all actively sending and requesting data and actions. Dr. Liu suggested that V2I communication could offer even greater options for these systems. Dr. Liu mentioned that his team participated in The University of Michigan Transportation Research Institute Safety Pilot, which incorporated V2I technology. For this study, he noted that the research team instrumented 19 intersections and plans to instrument up to 60 intersections and 9,000 vehicles. Their goal is to expand the testbed to southeast Michigan and, in time, have the infrastructure to communicate speed advisories and rerouting information.

New Applications for Infrastructure-Based Sensor Data

Walton Fehr
Program Manager, U.S. Department of Transportation's Intelligent Transportation Systems Joint Program Office

Overview

During his presentation, Walton Fehr discussed the cooperative, communication-based, intelligent transportation system (ITS) technology pilot, conducted by the University of Michigan's Transportation Research Institute in 2013 (also known as the Safety Pilot Model Deployment). He stated that the pilot study investigated the benefit of communication-based ITS on crash avoidance. Fehr noted that the results of this pilot led the National Highway Traffic Safety Administration to investigate rulemaking that would require communication technology in all new vehicles. He mentioned that there will be a large round of deployment trials and more information can be found at http://www.its.dot.gov/pilots/.

Major Themes Discussed

Fehr discussed several themes during his presentation. He highlighted several requirements that a system such as the ITS technology pilot would require to have in place before moving forward. These requirements include establishing a common process for all information flows that preserves privacy and security; ensuring availability of data for all users of the transportation system ubiquitously and in a standard form that makes use of many different types of media, including dedicated short-range communications; and safeguarding conservation of privacy for consumer acceptance.

Next, Fehr mentioned that the U.S. Department of Transportation's (USDOT's) ITS Joint Program Office (JPO) developed a reference implementation architecture to support all of the above requirements. Fehr noted that outreach is a major part of this effort and includes the following:

- Engaging stakeholders to familiarize people with this work and secure their input.
- Holding events with ITS JPO support staff, where participants connect via the Web to data-movement demonstrations.
- Documenting the communications standards used in the reference architecture to build a common understanding among all users.

Fehr highlighted that USDOT entered into more than 62 memoranda of agreement with public, private, and academic organizations as affiliated testbed collaborators. This status allows outside parties, with no previous connection to FHWA, to participate in and follow activities surrounding the reference implementation architecture as they occur. Fehr noted that the ITS JPO developed a data-flow visualizer online that all of these members may access. He explained that there are three different types of fundamental data flows that the ITS JPO is trying to understand to help them build the reference architecture, as follows:

1. **Traveler Situation**. This involves actionable information that travelers should have at their disposal, flowing from the transportation system managers to the vehicle.
2. **Field Situation**. This involves control devices that exist at the boundary between mobile and fixed elements, such as traffic-signal controllers, which direct data from the field equipment to both the transportation system managers and the vehicles.
3. **Vehicle Situation**. This data originates in the vehicle and flows to field devices or the back offices.

Data Management

Fehr then discussed what is required to measure data quality. He suggested that a basic safety message, containing vehicle safety-related information that is periodically broadcast to surrounding vehicles, is required to meet performance requirements. He also suggested there needs to be a common interpretation of standards, for example among geometric intersection data, mobility application programs, and signal phase and timing. Fehr mentioned that every data unit must meet the fundamental performance requirement, in that it must be operable in every situation. He noted that traveler situation data should also be delivered to USDOT's data distribution warehouse using an agreed format. This would enable USDOT to make the data available in different ways to data users.

Fehr noted that USDOT is keeping track of all of the data contributions and users so that, sometime in the future, there can be a market built around it. Fehr also noted that the ITS JPO created a traveler situation data tool that helps practitioners create data units and deliver them to the distribution warehouse. The tool automatically encodes the data according to USDOT standards. In summary, Fehr highlighted that V2I and V2V communication is extremely important for traffic control and will continue to be important as automation technology in vehicles becomes available.

Data Standards and Sensors

PANELISTS

Dr. Christos Cassandras
Professor of Electrical and Computer Engineering, Boston University

Richard Denney
Operations Specialist, FHWA Resource Center

Dr. Stan Young
President, Traffax, Inc.

MODERATOR

Cathy McGhee
Virginia Department of Transportation

Controlling Traffic Networks

Dr. Cassandras addressed the challenges of controlling traffic networks and described some of his efforts to improve the accuracy of data to overcome these challenges. Dr. Cassandras explained that, even though the achievable optimum of a network can be calculated, it is still very hard to control traffic networks. He noted that one reason for this is that there are not enough controls in the system (e.g., traffic signals and tolls) and this leaves little opportunity to provide feedback. Dr. Cassandras mentioned that another reason is that drivers do not know what the other drivers are doing. This can lead to poor decisionmaking where drivers act in ways that will benefit themselves, which is in conflict with those actions that will optimally benefit the system.

Dr. Cassandras highlighted that innovative sensor technology, and the data it produces, have the potential to overcome some of these challenges by creating smart transportation systems. He noted that sensors can be infrastructure-based, such as inductive loops, and camera- or imaging-based sensors, which are commonly used today. Dr. Cassandras suggested that another method is to use GPS and accelerometers in mobile phones and vehicles as sensors without any requirement for additional infrastructure. These types of sensors can provide status information such as vehicle position, velocity, destination, fuel level, and battery level. Dr. Cassandras noted that the accuracy of data is important and essential to creating smart systems and implementing successful real-time traffic control. He provided an example from his research to show how a smart-parking system using cameras and loop detectors, which are a low-cost solution, can produce accurate data with minimal delay (shown in figure 3).[2]

Dr. Cassandras mentioned that a challenge facing researchers in this field is to find new mechanisms to control traffic based on data collected through sensors. He highlighted some research projects he is working on to achieve this, as follows:

- **Adaptive traffic-signal control**. This system collects queue data in real time and adjusts traffic signals accordingly to reduce vehicle delay.
- **Quasi-dynamic control**. This system uses queue thresholds to compare queues on one street to another and changes the traffic signal accordingly. This technique shows a nine-fold decrease in congestion in computational simulation but must be done in real time.

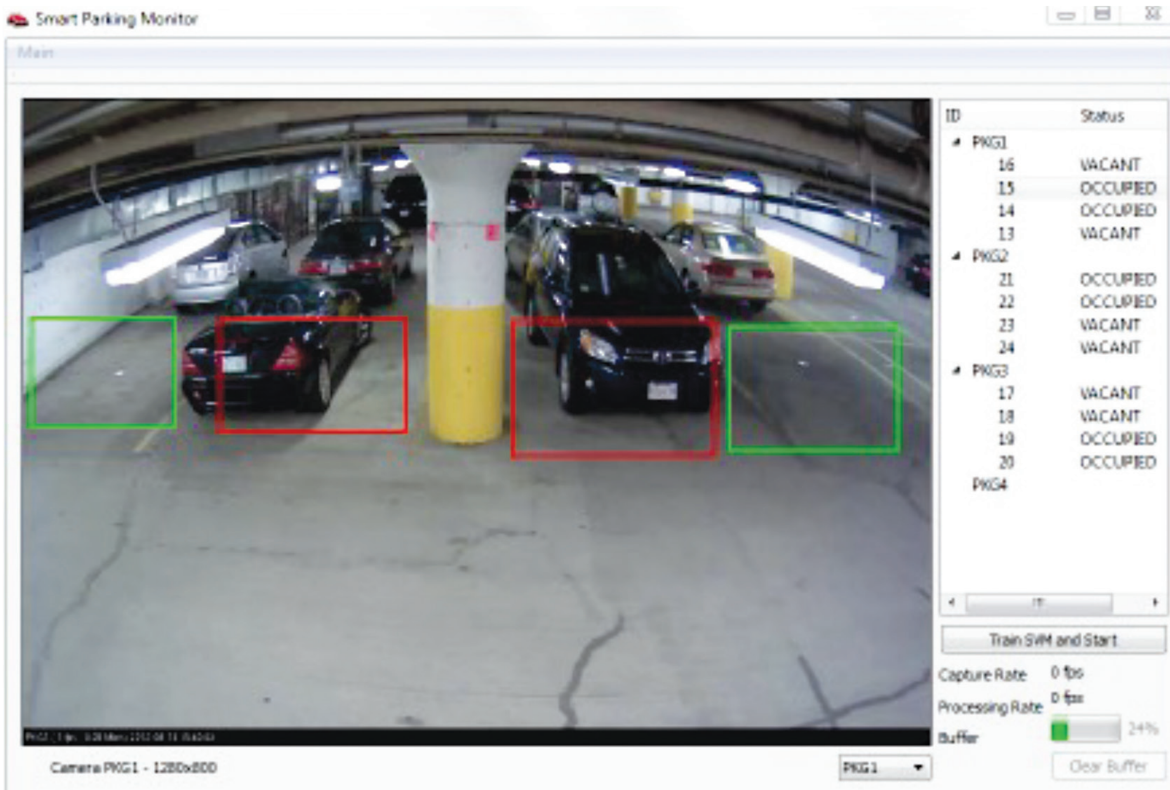

Figure 3. Wireless loop detectors used for a smart-parking system.

Using Sensor Data

Richard Denney discussed how to use sensor data to create new standards that are useful for next generation control systems. He noted that the purpose of today's traffic sensors is simply to call and extend the green phase of the signal. Control systems have been built around reducing complaints from drivers about waiting at signals too long, waiting at queues that back up too far, or stopping at too many traffic signals. Denney highlighted that calling and extending green phases do not require distinguishing one car from another, therefore these detectors are not useful for counting cars. He noted that the purpose for counting cars is to feed traffic-simulation models. However, that application for the data has not proven sufficiently valuable to motivate industry to develop the capability for sensors to accurately count cars.

Denney suggested that there is a need to establish how data taken from sensors can be made more actionable. For example, the data could be used to optimize traffic in a way that allows queues only in areas where they will cause the least performance degradation. Denney highlighted that, to take advantage of new detection technology, new use cases must be developed. He noted that part of developing the use case is understanding what needs to be optimized. These use cases must be clearly defined and helpful for today's uses.

Using Reidentification Data

Dr. Young presented on the importance of reidentification of data and how it can be used to produce useful data. Dr. Young noted that Bluetooth and other reidentification data provide broad-based travel-time data that do not have to be modeled to obtain a good sample. The resulting travel-time distributions allow for a detailed interpretation of intersection performance. Dr. Young highlighted that the data are comparable in accuracy to outsourced probe data. He suggested that travel time is particularly relevant because it is what the user experiences directly.

Dr. Young then showed workshop participants a cumulative distribution function (CDF) of sampled travel-time data, which can be used to compare information such as before-and-after signal timing and phasing of signals (shown in figure 4). He noted that travel time is the standard metric for assessing performance and highlighted that the desired way of measuring travel time is with a CDF because it facilitates comparison of before-and-after scenarios, different signal-timing approaches, and different facilities. In addition, it also shows degradation of performance over time. Dr. Young mentioned that a challenge for researchers is quantifying good or poor performance based on the CDF.

Dr. Young noted that the methods outlined in his presentation work well for highways but industry does not yet know how to model an arterial management system and has not come to a consensus on effective performance measures. He suggested that travel time needs to be expressed in a way that can be understood by those who make decisions about funding.

Dr. Young also described a recent project that aims to validate outsourced probe data by comparing them to a reference dataset. The project is focused on the Interstate-95 corridor in Pennsylvania, and there are three vendors that are online and collecting data. Dr. Young mentioned that the datasets from each vendor are very similar to one another and to the reference dataset. He stated that this means that outsourced probe data are effective at capturing vehicle congestion on interstates.

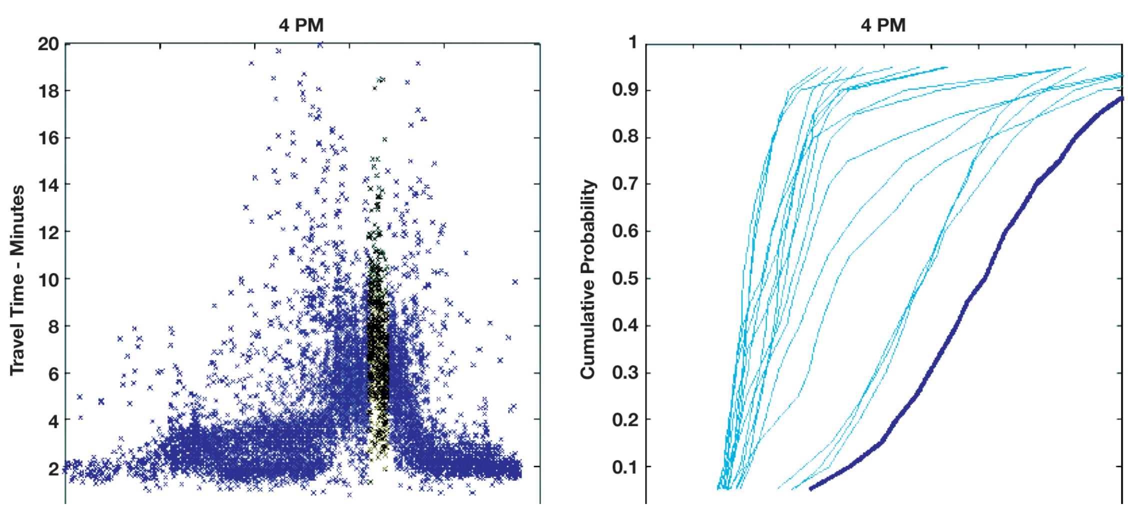

Figure 4. Cumulative distribution function from sampled travel-time data.
Note: black data points on the left chart highlight the 4–5 PM peak hour, which has the greatest delay. This corresponds to the curve highlighted in the chart on the right.

Day Two:
Next Generation Signal Control System Algorithms

Day Two Introduction

David Gibson at FHWA began the second day of the workshop with a brief summary of the previous day's presentations and discussions. He noted that control-system layouts of the past are now obsolete because the sensor landscape has changed over time to include technology such as Bluetooth sensors, vehicle reidentification, and dedicated short-range communications. Gibson mentioned that data fusion is an important part of improving algorithms and, for control systems, it is important to understand what to optimize. He suggested that, for both sensors and control algorithms, it is important to have a simulation and optimization framework to support research.

Gibson continued to explain that researching and developing new traffic-signal control algorithms requires a fairly complex simulation infrastructure. The demands of assembling the infrastructure often lead researchers to spend more time on the infrastructure than on the core question of control algorithm development. Challenging issues with intellectual property rights also remain, suggesting the need for open source approaches. The second day of the workshop aimed to accelerate the development of tools for future signal control research by confirming the need for and potential benefits of these tools and considerations for their development and dissemination.

Presentations and facilitated discussion from the second day of the workshop are summarized in the following section.

What is Wrong With Today's Traffic Control Systems?

Dr. Larry Head
Associate Professor of Systems and Industrial Engineering and Engineering Management, University of Arizona

Overview
Dr. Head presented several challenges to workshop participants that are associated with traffic control systems. These challenges are outlined in the following section.

Challenge 1: Configuration Management
Dr. Head highlighted that configuring traffic-signal control systems properly is critical to getting them to perform properly; however, he also noted that there is not a reliable way to know which intersections are configured poorly. The current method requires a test vehicle to actuate the detector in the field. Dr. Head suggested that this is not a cost-effective method and there must be a better way to move forward. He noted that personnel need to be trained to configure the systems properly and certification might be necessary. Dr. Head also mentioned that security is an issue and will be especially important as connected vehicles roll out.

Challenge 2: Detection
Dr. Head noted that practitioners need to not only know how to assess and use detection data but also how to make detectors more reliable and available. He suggested that researchers should think differently about detection methods for intersections and freeways. Dr. Head mentioned that different technologies could be explored, such as light detection and ranging and ultrasound. He highlighted that video technologies at intersections could also give good situational awareness and clear images of the environment. Dr. Head emphasized that different technologies are useful for different objectives.

Challenge 3: Performance Measurement
Dr. Head suggested that there may be more useful performance measures beyond the traditional methods, such as delays, stops, and travel time. He mentioned that a useful metric could be to measure the number of controllers or detectors that are working properly, or to measure availability, reliability, and quality. Dr. Head noted that measuring delay and travel time does not indicate how well the system is functioning. He also noted that many different metrics are required to operate the system, such as turning-movement counts, phase-demand volume, and physical geometry.

Challenge 4: Control Algorithms
Dr. Head noted that practitioners need to maximize the usefulness of their controllers. He described how traffic controllers have many features that are highly specialized but operators do not always know about all of the different features. Dr. Head provided the example of how fixed-time control works well in a central business district but it is not necessarily good for other situations. In addition, Dr. Head mentioned that

actuated and coordinated actuated signals work well to minimize phase failures but are not effective in congested conditions. These signals also depend on the detection system reliability. Dr. Head highlighted that there are a lot of parameters to consider and they must be configured properly to optimize performance.

Challenge 5: Multimodal Control

Dr. Head highlighted that there are many different users of the transportation system, each with their own set of requirements, which result in competing interests. He noted that most traffic control systems treat modes other than passenger vehicles as local exceptions. As an example, Dr. Head reminded workshop participants that pedestrians have to push a button to actuate the signal. He noted that coordinating all of the modes in practice on a corridor scale is rare and difficult.

Suggested Research Topics

Dr. Head proposed several research topics, including longer term and higher risk research topics, as follows:

- Analyze reliability of and requirements for system components.
- Monitor detectors and sensors and estimate their remaining useful life.
- Use data from geometrically distributed sensors to check validity of data.
- Implement sensors for situational awareness at intersections that can respond to different modes and changing dynamics.
- Investigate control algorithms that can adapt to loss of information or multimodal requirements.
- Develop optimization tools that can take trajectory inputs.
- Use technology to measure conflicts as a surrogate for safety to balance safety and efficiency.

In summary, Dr. Head reminded workshop participants that adaptive controllers have the capability to learn how the intersection works instead of relying on pre-programming. He highlighted that there are too many parameters to adjust and features that are specific to special situations or particular modes. Dr. Head suggested that this makes configuration so complicated that most people do not understand how to do it well. He noted that controller configuration could be made simpler.

Using Analysis and Information in Control Systems

Dr. Steve Remias
Transportation Research Engineer, Department of Civil Engineering, Purdue University

Overview
During his presentation, Dr. Remias described the evolution of transportation operation from fixed time, to actuated, to adaptive control.

Major Themes Discussed
Dr. Remias discussed several themes during his presentation. He noted that there is a misconception that adaptive is a "set it and forget it" controller. He suggested that the situation is more complicated than that. Dr. Remias highlighted that performance measures are complex and need to be actionable and there is no single measure that can tell us everything. He mentioned that a set of performance measures will provide a comprehensive picture and these performance measures must go back into the system and be reinforced when performance is good.

Dr. Remias also discussed signal timing and noted that it is a six-step process. He focused on the final step in this process, which is the assessment step. This refers to the types and quality of data that are used. Dr. Remias noted that the results of the assessment will provide feedback for the system. He also noted that high-resolution signal-control data capture can collect data any time the signal state changes or if a vehicle is detected. Dr. Remias mentioned that this is very useful. He noted that all of the controller manufacturers at this time implement this in different ways but these differences are still being worked out. He also mentioned that it is now possible to embed equipment that collects high-resolution signal-control data.

Current Projects
Dr. Remias highlighted several relevant projects at Purdue University, as follows:

- Indiana Department of Transportation (DOT) installed Bluetooth stations that compute real-time travel times. Dr. Remias noted that Bluetooth allows the MAC (i.e., machine access code) address of a device to be identified several times along the corridor.
- Researchers aggregated crowdsourced probe data based on cell-phone data into average speeds per segment and per minute.
- Purdue University developed some performance measures that use data fusion. Researchers will investigate controller and probe data to quantify what is observed in the field and assess how to improve it.

- Purdue University developed a coordination diagram (shown in figure 5) that allows for correlation between detection and the green time of the phase to estimate the number of arrivals on green.
- Indiana DOT used Bluetooth to identify the cause of a problem on a corridor that was not performing properly. Indiana DOT researchers used the probe data to determine location and time and used high-resolution control data to determine why.
- Researchers for an arterial retiming analysis study, conducted in Indiana, used crowdsourced probe data to successfully improve average travel time but not travel-time reliability.

Future Research and Near-Term Opportunities

At the conclusion of his presentation, Dr. Remias identified some near-term research opportunities, as follows:

- Identify ways to help practitioners understand the performance measures that are being developed.
- Develop business practices that get vendors and practitioners involved.
- Support the implementation of performance measures.

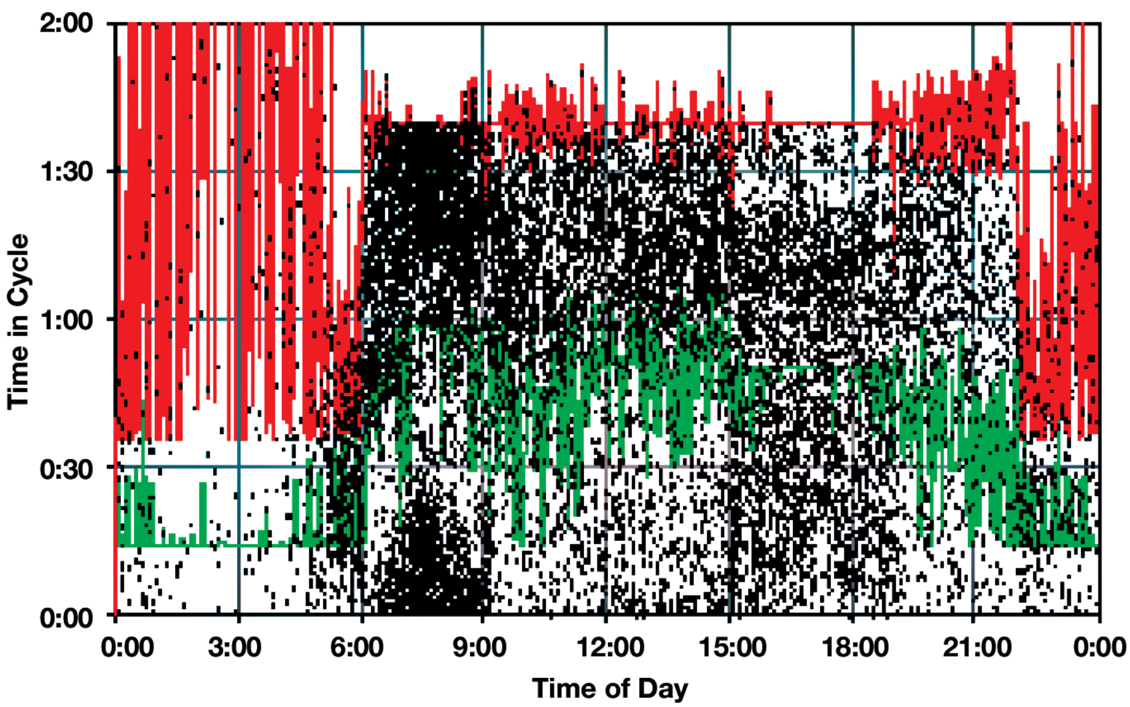

Figure 5. A coordination diagram developed by Purdue University.
Note: black dots represent vehicle arrivals; the different phases of the cycle are represented by red and green.

Making Something Work: The Academic and Industry Perspectives

Dr. Pitu Mirchandani
Professor of Computing, Informatics, and Decision Systems Engineering, Arizona State University

Dr. Steve Shelby
Senior Research Engineer, Econolite Group, Inc.

MODERATOR
Raj Ghaman
Texas Transportation Institute

Overview
The next two presentations provided perspectives from academic and industry representatives involved in adaptive traffic control.

Academic Perspective
Dr. Mirchandani explained that when there is little fluctuation between supply and demand in transportation, the system moves toward equilibrium. He noted that this is rarely the case and suggested that fluctuations can be dealt with either proactively or reactively. Dr. Mirchandani suggested that sensors, communication infrastructure, central processing units, and engineers are necessary to be proactive. Dr. Mirchandani also mentioned one of his projects that streams real-time field data to a bank of servers in a cloud and makes predictions and adjustments by using a cyber-physical system, known as *managing interactive demands and supplies (MIDAS)*. He noted that MIDAS uses big data, real-time algorithms, and cloud computing to proactively manage traffic, as shown in figure 6.

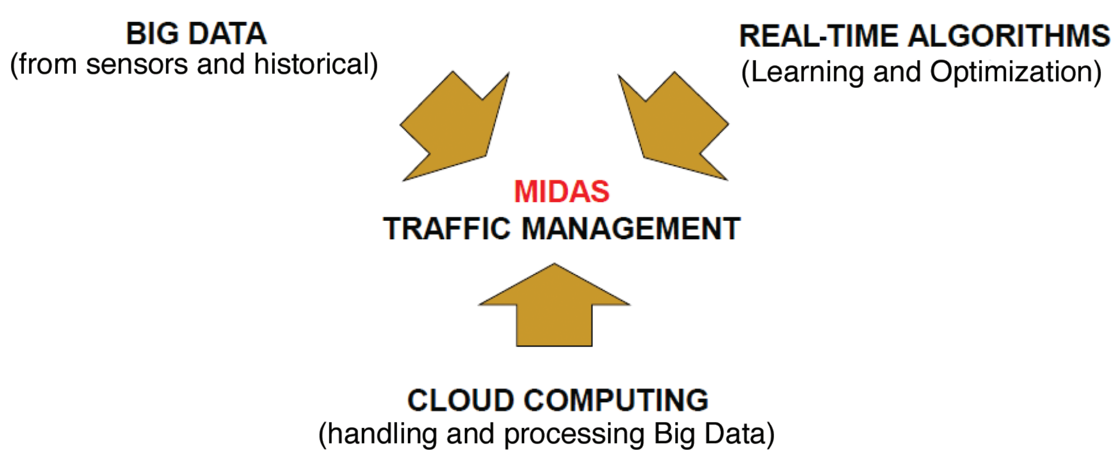

Figure 6. An overview of managing interactive demands and supplies.

Dr. Mirchandani explained that, in proactive control, sensors are used to measure the outputs of the system, and then models perform the estimation. He mentioned that decisions are made and controls are based on these decisions. He highlighted several features of proactive traffic control, including that it:

- Explicitly recognizes that traffic state is a nonstationary stochastic process.
- Requires prediction of short-term future based on current conditions and controls.
- Is especially useful for nonrecurrent traffic conditions and major incidents.
- Requires constant monitoring and prediction of traffic performance.

Dr. Mirchandani noted that MIDAS focuses on lanes instead of links. He explained that fluid flow, in relation to traffic-flow theory, does not consider that freeways have lanes that may have different types of vehicles (e.g., automated or connected). He suggested that predictions must be made about what is happening in lanes and that this can produce lane-based real-time speed maps, which are better than aggregate predictions and allow for managed lane predictions.

Dr. Mirchandani described a control system that he developed called the *real-time hierarchical optimized distributed effective system (RHODES)*. He highlighted that the system proactively predicts demand at traffic signals. It is based on a real-time feedback control paradigm, will work with multiple modes, and is applicable to intersections, arterials, and networks. Dr. Mirchandani explained that RHODES uses discharge rates, travel times, and turn ratios to predict arrivals and queues, which then feed a control algorithm. He described how this algorithm, known as the *categorized arrivals-based phase re-optimization at intersections control algorithm*, is a real-time algorithm that determines the duration of the different phases of the signal, allows various objectives (e.g., optimization of the delay) to be programmed for different vehicle classes, considers categories of predicted arrivals and their objectives, and considers a given rolling decision time horizon with time increments in seconds. Dr. Mirchandani noted that RHODES enables a user to compute total delay and stops over an entire corridor with many intersections.

Dr. Mirchandani also introduced workshop participants to the next generation of RHODES, known as *self-tuning RHODES*. He explained that the performance of RHODES is directly related to the accuracy of its queue estimates, which are dependent on parameters that are not fixed (e.g., turn proportions, queue-discharge rates, and link-travel times).

At the conclusion of his presentation, Dr. Mirchandani noted several general research observations, as follows:

- Demands can be managed through congestion pricing, incentives, and rewards on a real-time basis.
- Data from GPS and Bluetooth can provide the percentage of vehicles demanding different signal services, which can then be fused with other data to make predictions for demand of various signal services. Dynamic programming can be used to make self-adaptive decisions.

He also made the following concluding remarks:

- Improvement in traffic performance proactively responds to:
  - o Recurrent congestion.
  - o Near oversaturation.
  - o Nonrecurrent conditions and incidents.
- Performance measures obtained from proactive-traffic control allow for a decrease in traffic management and planning efforts.
- In the near future, the supply side of transportation will be operated, and the demand side will be influenced, to improve service for special vehicles (e.g., emergency, transit, and hazardous materials).
- Vehicles may opt in for being tracked in the network in exchange for improved service.

Industry Perspective

Dr. Shelby explained that traffic management systems in the future will be able to obtain better information about vehicles in the network, which will enable more capable adaptive control. He noted that connected vehicles will arrive soon, broadcasting real-time location information, and suggested that this will transform how optimization algorithms work.

Dr. Shelby highlighted that it was approximately 20-years ago that FHWA unveiled the real-time traffic adaptive control system program. He reminded workshop participants that it is important to understand key findings from adaptive control research in the past 20 years, in both academia and industry. He highlighted that this informed perspective suggests more practical expectations for the future. Dr. Shelby noted that the work of adaptive control proved to be a challenging multidisciplinary endeavor. He mentioned that, of the five groups funded by FHWA under the real-time traffic adaptive control system program, three groups produced functional software. Of these three prototypes, one demonstrated performance benefits in an independent traffic simulation evaluation, and none produced significant performance benefits versus traditional time-of-day control in field operational tests. Dr. Shelby noted that when traffic was not heavy, there were no pedestrians, and the system was unconstrained in terms of phase sequencing, the real-time adaptive signal control system performed very well. However, he highlighted that the system did not perform well when traffic was heavy, if there were regular pedestrians actuating “WALK” signal timing, if the adaptive control system was constrained in terms of the phase sequence, or if it was not allowed to skip phases based on demand from pedestrians or vehicles.

Dr. Shelby suggested a need to consider longer time horizons for optimizing traffic flow. He mentioned that planning a full cycle ahead (in this case, over 100 seconds) is a challenge for acyclic adaptive control systems and computational effort grows very fast as a function of the optimization horizon. Unlike cyclic systems, which distribute time cyclically to each phase of the intersection, acyclic systems decide every time whether to switch or not to switch to the next phase. Dr. Shelby highlighted that perfect information does not overcome the fundamental challenges of a problem and, while it helps, it does not yield a paradigm leap over traditional control. He noted that, even with perfect information, the computational complexity of the optimization still requires time-saving optimization shortcuts that can degrade performance. Dr. Shelby also mentioned that predicting arrivals on the order of a large cycle length is still a problem because those vehicles still have to drive through several other acyclic adaptive signals before they will arrive.

He noted that agencies are very cost sensitive and will not adopt new technology unless it is cost effective and adds value. He also noted that agencies did not embrace adaptive control systems because they were expensive, complex, and did not consistently improve traffic flow relative to traditional nonadaptive signal timing. He suggested that, because agencies are so sensitive to cost, value considerations may influence perspectives on what types of future research might be more practical and valuable. He highlighted that even with a mandate for all newly manufactured vehicles to broadcast location, there would still be a requirement for infrastructure-based sensors to see and serve "unconnected" vehicles, bicycles, and pedestrians.

Dr. Shelby highlighted that the next generation of sensors will provide object-tracking capability instead of just zone-presence capability. He mentioned that, whether it is through light detection and ranging, radar, or another technology, the next generation is likely to overcome some of the detection problems attributed to night time, glare, shadows, fog, or other issues that hamper video detection today. He suggested that adaptive control could benefit from more accurate sensors but, as referenced previously, even perfect information is not going to substantially change performance at typical intersections during typical conditions.

Tool Applications and Development Considerations

Edward Fok
Transportation Technology Specialist, FHWA Resource Center

Dr. Douglas Gettman
Systems Manager, Kimley-Horn and Associates, Inc.

MODERATOR
Deborah Curtis
Federal Highway Administration

Overview

The next two presentations discussed tool considerations for advanced traffic control systems and tools for performance assessment and agency application development issues.

Tools for Advanced Traffic Control Systems

Edward Fok suggested several requirements for successful traffic control. He mentioned that it is important to consider end users and their goals, limitations, and concerns. Fok noted that safety is a goal that is the combined responsibility of the vendor and the agency. Operators need to make sure their systems are used correctly, and this places constraints on the system. He noted that safety needs to be guaranteed by vendor, manufacturer, and software supplier. Fok highlighted that mobility is another goal that requires a lot of data to meet. He suggested that there needs to be a case made for keeping and using the data so that agencies prioritize doing so. Fok also highlighted that accountability is important to agencies, so that they know that a tool is doing what it is supposed to be doing. He noted that the privacy issues related to large datasets also need to be resolved.

Fok also suggested some capabilities and limitations for workshop participants to consider, as follows:

- Does an agency understand how a tool works?
- How much training and hardware investment is required to use the tool?
- Are the skillsets transferable and how long does it take to get staff trained with the tool?

Fok also highlighted that the return on investment needs to be understood for safety, mobility, and staff investment and metrics need to be established to show this return.

Tools for Performance Assessment

In the next presentation, Dr. Gettman discussed some of the barriers to adaptive control, including cost and uncertainty of benefits. He mentioned that previous work addressed some of the cost-barrier issues. He also highlighted a current effort with FHWA, as part of the Every Day Counts initiative, to address some of the issues with respect to uncertain benefits. He noted that the goal is to get proven technologies used more often in industry and adaptive signal control was one of the selected programs. Dr. Gettman attributed uncertainty of benefits to the following factors:

- Wrong objectives.
- Wrong measures of effectiveness (MOEs).
- Different baselines.
- Limited validation process.

Dr. Gettman noted that adaptive control can sometimes produce false good results. He mentioned that this could happen because the inputs are bad, the results are cherry picked, or if the traffic is changing. He also noted that at other times the adaptive control performance may influence results.

Dr. Gettman highlighted that industry is developing tools for deploying adaptive systems. These tools include Bluetooth sensors, smart phones, traffic counters, and controllers to collect data that are processed to generate MOEs. Dr. Gettman mentioned several available MOEs, including percent of arrivals on green, platoon ratio, green-occupancy ratio, reliability, throughput, route-travel time, route-travel delay, travel-time reliability, and stops per mile. He also mentioned some MOEs for future use, including emissions, regional aggregates, charts or graphs, and dashboards.

At the conclusion of his presentation, Dr. Gettman outlined some additional thoughts, as follows:

- The USDOT's Open Source Application Development Portal is a Website where developers can upload code. The site can be viewed at http://itsforge.net/. Dr. Gettman mentioned that some operating systems have a hard time with open source, so this is a limitation. He suggested that agencies will need assistance to implement open source applications.
- Agencies will need help and education on the functionality of different types of software with respect to features such as big data and cloud storage. Dr. Gettman noted that traffic managers need to know how to use this software to manage data.
- Agencies spend their time in their localities. Dr. Gettman noted that they need resources they can rely on to hear about what their peers are doing.

Facilitated Discussion—Final Takeaways

At the conclusion of the workshop, David Kuehn, EAR Program Manager, facilitated a group discussion about what was learned at the workshop. The key discussion points and final thoughts of workshop participants are summarized in the following section.

Building Off What We Have

- ***Address the state of practice***. It is not feasible to ask agencies to replace all of their controllers. The overlays need to have failsafe modes that would revert back to today's system in the event of failure. Investigators must establish what it would take to get today's system to be 100-percent reliable. A first step is to characterize reliability and establish the quality expectation and the level of accuracy required to detect a vehicle.
- ***Address vehicles without sensors***. Infrastructure-based sensors are needed for those vehicles that do not have sensing technology.
- ***Continue to use existing systems***. The current traffic-signal control systems work well and are safe at moderate loads. These should continue to be used. The challenge is eliminating congestion.

New Kinds of Data

- ***Characterize performance***. There will be a shift in the kind of data received, and researchers need to change the way that performance is characterized. It may be possible to characterize performance measures and optimize results with trajectory-based data. This is the type of data that new sources will produce and the distributed algorithms will eliminate the need for data collection and centralized control.
- ***Develop new sensor networks***. There is a need to develop sensor networks using data that are outputs from vehicles.

Using Data More Effectively

- ***Improve control***. There is a need to identify how to use data to better control vehicles.
- ***Provide network information***. Investigators need to empower travelers about how, when, and what mode they choose. The more information about the network that travelers have, the more effective their decisionmaking will be. The only control at the moment is when and where to stop cars to avoid conflicts; in the future this will extend to slowing and organizing cars. There are other existing controls to harness in the meantime (e.g., congestion pricing).
- ***Improve congestion pricing***. Next generation traffic control does not only apply to traffic-signal control. Major cities use congestion pricing, and all major cities

use radio reports to report congestion. The next generation may use point-to-point communications to make these techniques more precise.

- ***Ensure safety***. Sensor resources have to be dedicated to those systems that ensure safety.
- ***Work with the user***. Video data are important for detection, but for signal control, investigators need to find a balance between adaptive and cooperative. Users cannot be eliminated and investigators need to find a way to make them useful.
- ***Improve sensors***. Investigators could fuse multiple sensor technologies for better operation and function.
- ***Expand the user base***. Investigators need to examine what data and information can be better used by others outside of the traditional domain to improve the business case for data management.
- ***Assess previous traffic***. Investigators could advance intersection control based on traffic history or platoons passing through the corridor.

Engaging with Practitioners—Shorter Term

- ***Improve productivity***. There is a need to focus on improving the productivity of operators.
- ***Improve education***. There is a need to educate those who maintain the equipment. Environmental conditions are different across the country, so it is important to identify the major problems and needs in different areas.
- ***Follow standards***. It is critical to ensure that industry standards are followed.
- ***Gauge effectiveness***. Methods and performance measures need to be established to gauge effectiveness for industry and customers.

Appendices

APPENDIX A: AGENDA

Day One: Next Generation Sensors		
Time	**Topic**	**Speaker(s)**
8:30–9:15 a.m.	Welcome EAR Program Overview FHWA Interest in Traffic Operations Workshop Introduction	David Kuehn Joe Peters David Gibson
9:15–10 a.m.	Presentation: How Can Advances in Science and Technology Enhance or Supplant Current Sensors or Control Systems?	Jakob Eriksson
10–10:15 a.m.	**Break**	
10:15–11:45 a.m.	Panel Discussion: Advances in Infrastructure-Based Sensors *Moderator: Raj Ghaman*	Lianyu Chu and Henry Liu
11:45 a.m.–1 p.m.	**Lunch**	
1–2 p.m.	Presentation: New Applications for Infrastructure-Based Sensor Data	Walton Fehr
2–2:15 p.m.	**Break**	
2:15–3:45 p.m.	Panel Discussion: Data Standards and Sensors *Moderator: Cathy McGhee*	Christos Cassandras, Richard Denney, and Stan Young
Adjourn		

Day Two: Next Generation Signal Control System Algorithms		
8:30–9 a.m.	Welcome and Recap of Day One	David Gibson
9–10 a.m.	Presentation: What is Wrong with Today's Traffic Control Systems?	Larry Head
10–11 a.m.	Presentation: Using Analysis and Information in Control Systems	Steve Remias
11–11:15 a.m.	**Break**	
11:15 a.m.–12:45 p.m.	Panel Discussion: Making Something Work: The Academic and Industry Perspectives *Moderator: Raj Ghaman*	Steve Shelby and Pitu Mirchandani
12:45–1:30 p.m.	**Lunch**	
1:30–3 p.m.	Panel Discussion: Tool Applications and Development Considerations *Moderator: Deborah Curtis*	Douglas Gettman and Edward Fok
3–3:15 p.m.	**Break**	
3:15–3:45 p.m.	Facilitated Discussion: Reflections on and Lessons from the Workshop by Participants	*David Kuehn, Facilitator*
3:45–4 p.m.	Closing: Next Steps	David Gibson
Adjourn		

APPENDIX B: PARTICIPANT LIST

Name	Affiliation
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Saad Bedros	University of Minnesota
Christos Cassandras	Boston University
Jimmy Chu	Federal Highway Administration
Lianyu Chu	CLR Analytics, Inc.
Deborah Curtis	Federal Highway Administration
Richard Denney	Federal Highway Administration
Jakob Eriksson	University of Illinois, Chicago
Walton Fehr	U.S. Department of Transportation
Robert Ferlis	Federal Highway Administration
Edward Fok	Federal Highway Administration
Stuart Gagnon	Federal Highway Administration
Douglas Gettman	Kimley-Horn & Associates, Inc.
Raj Ghaman	Texas Transportation Institute
David Gibson	Federal Highway Administration
Terry Halkyard	Federal Highway Administration
Larry Head	University of Arizona
Peter Huang	Federal Highway Administration
Zhitong Huang	Mississippi State University

APPENDIX B: PARTICIPANT LIST, cont'd.

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Kunik Lee	Federal Highway Administration
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Nicholas Maxemchuk	Columbia University
Cathy McGhee	Virginia Department of Transportation
Ben McKeever	Federal Highway Administration
Pete Mills	Federal Highway Administration (retired)
Pitu Mirchandani	Arizona State University
Jon Obenberger	Federal Highway Administration
Joe Peters	Federal Highway Administration
Jeremy Raw	Federal Highway Administration
Steve Remias	Purdue University
Ziad Sabra	Sabra, Wang & Associates, Inc.
Steve Shelby	Econolite Group, Inc.
Steven Smith	Carnegie Mellon University
Yubian Wang	Federal Highway Administration
Stan Young	Traffax Inc.
Li Zhang	Mississippi State University

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About the EAR Program

Federal legislation establishes an Exploratory Advanced Research (EAR) Program for transportation to address longer term, higher risk, breakthrough research with the potential for dramatic long-term improvements to transportation systems, improvements in planning, building, renewing, and operating safe, congestion-free, and environmentally sound transportation facilities. The Federal Highway Administration's (FHWA's) EAR Program secures broad scientific participation and extensive coverage of advanced ideas and new technologies through stakeholder engagement, topic identification, and sponsored research. The uncertainties in the research approach and outcomes challenge organizations and researchers to be innovative problem-solvers, which can lead to new research techniques, instruments, and processes that can be applied to future high-risk and applied research projects.

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