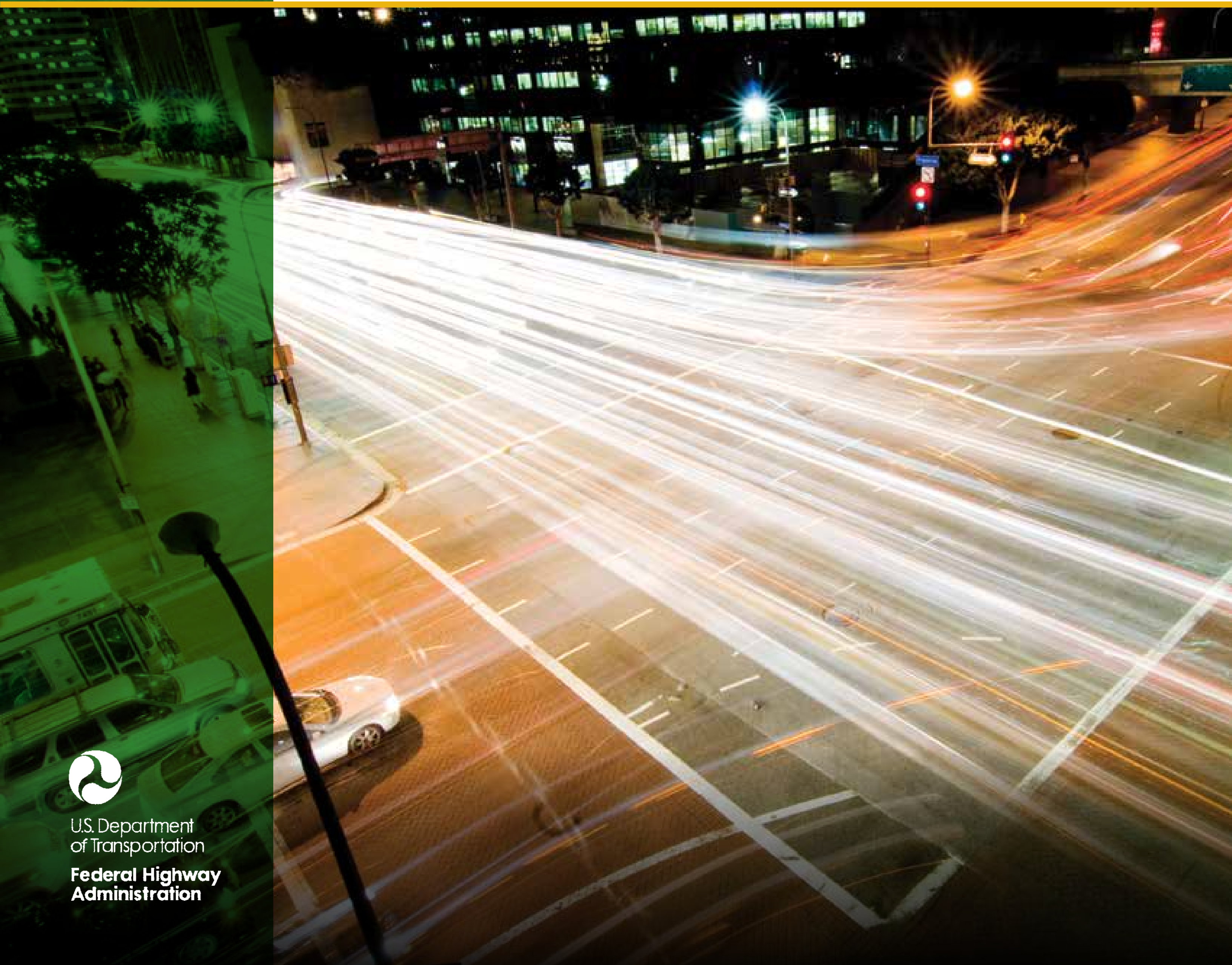
The Exploratory Advanced Research Program

EXPLORATORY ADVANCED RESEARCH

Breakthroughs in Vision and Visibility for Highway Safety

WORKSHOP SUMMARY REPORT • AUGUST 13–14, 2014



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16. Abstract
On August 13–14, 2014, at the Turner–Fairbank Highway Research Center in McLean, VA, the Federal Highway Administration's (FHWA's) Office of Safety Research and Development and the Office of Safety, with support from the Exploratory Advanced Research Program, convened a 2-day workshop, "Breakthroughs in Vision and Visibility for Highway Safety." Investigators have previously conducted research in a variety of areas surrounding visibility issues, including efforts exploring retroreflectivity and pavement-marking signs, and legibility of fonts; however, much of this work has been tapering off. The objective of this workshop was to identify gaps in highway visibility research, explore innovative tools and techniques to fill these gaps, and determine the role for FHWA.

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Vision, visibility, highway, safety, lighting, luminance, retroreflectivity, pavement marking, driver safety, eye-movement analysis, signage, fonts.

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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)

Executive Summary

On August 13–14, 2014, at the Turner–Fairbank Highway Research Center in McLean, VA, the Federal Highway Administration's (FHWA's) Office of Safety Research and Development (R&D) and the Office of Safety, with support from the Exploratory Advanced Research (EAR) Program, convened a 2-day workshop, "Breakthroughs in Vision and Visibility for Highway Safety." Michelle Arnold of FHWA's Office of Safety R&D Human Factors Team provided a brief introduction describing the purpose of the workshop, after which Monique Evans, FHWA's Office Director for Safety R&D, formally welcomed workshop participants. In her welcome address, Evans stated that investigators have conducted research in a variety of areas surrounding visibility issues, including efforts exploring retroreflectivity and pavement-marking signs, and legibility of fonts; however, much of this work has been tapering off. Evans addressed the need to identify the role for FHWA in this particular field, what is needed, and where FHWA fits in.

Next, David Kuehn, EAR Program Manager, briefly discussed the purpose of the EAR Program. Kuehn began by stating that the EAR Program not only focuses on finding advances in science and engineering that have not been applied in transportation research, but also uses these advances to enhance the highway transportation safety system. He mentioned that there has been a lot of research conducted relating to visibility but that this research has focused on the energy sector and the vehicle side, as opposed to transportation infrastructure. Kuehn also noted that there have been several advances in sight and cognition research that move beyond the existing processes and framework used in highway visibility.

During day one of the workshop, participants observed presentations from five expert speakers operating in different fields related to visibility research. The speakers covered various topics, including FHWA's previous research, roadway-lighting limitations, and eye-movement analysis. Following the presentations, the panel of speakers and audience members discussed current issues in this area of research and identified research gaps that could help move the field forward.

On day two of the workshop, Cathy Satterfield at FHWA's Office of Safety provided workshop participants with a recap of day one and summarized the research that was presented by the five speakers. Following the recap, the workshop participants divided into two groups to discuss in detail the following two topics: (1) what exploratory research do we need to conduct to bring us into the future; and (2) how do we coordinate across disciplines?

The facilitator for the second day of activities asked each group to discuss what applied research is needed and identify next steps for future research. Following this, the workshop participants visited FHWA's Arens Photometric Visibility Laboratory. Researchers have used this laboratory to conduct a variety of studies, including evaluations of the photometric and colorimetric properties of traffic control devices. Researchers have also used the laboratory to investigate signage and pavement-marking materials and traffic signal lights. The workshop participants discussed possible ideas for use of the laboratory in the future.

Key discussion points from the workshop are summarized as follows:

- **Establishing standards.** Visibility standards and guidelines currently being used for new technologies (e.g., virtual windshields and head-up-displays that project information onto the windshield) and the roadway implications of these technologies (e.g., pavement markings, sign clutter, and billboards) need to be revisited and reestablished.
- **Researching decisionmaking.** Driver, pedestrian, and night simulation research are needed to provide insight into driver decisionmaking processes when visibility is low.
- **Understanding the impact of technologies.** Investigators need to conduct research that studies the effect of active safety and partial automation technologies on highway visibility (e.g., adaptive cruise control and lane-departure systems) and driver risk assessment.
- **Looking to future technologies.** Investigators need to identify research that bridges the gap between technology today (e.g., partial automation) and future technology (e.g., full vehicle automation).
- **Communicating research.** Government agencies, universities, industry, and other countries need more communication and research coordination to create a clearinghouse of current, ongoing, and relevant visibility research.

Table of Contents

List of Figures

List of Acronyms and Abbreviations

CALTRANS	California Department of Transportation
DOT	Department of Transportation
EAR	Exploratory Advanced Research
FHWA	Federal Highway Administration
GPS	global positioning system
HUD	head-up display
IFSTTAR	French Institute of Science and Technology for Transport, Development, and Networks
LED	light-emitting diodes
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
R&D	Research and Development
SEMs	saccadic eye movements
TTI	Texas A&M Transportation Institute
V2V	vehicle-to-vehicle

Introduction

On August 13–14, 2014, at the Turner–Fairbank Highway Research Center in McLean, VA, the Federal Highway Administration's (FHWA's) Office of Safety Research and Development (R&D) and Office of Safety, with support from the Exploratory Advanced Research (EAR) Program, convened a 2-day workshop, "Breakthroughs in Vision and Visibility for Highway Safety." The purpose of this workshop was to identify gaps in highway visibility research and brainstorm about innovative tools and techniques to fill those gaps. FHWA's Office of Safety R&D invited speakers from universities and research companies across the globe to present their research and to provide insights into next steps in highway visibility. The speakers also participated in a panel discussion with the other workshop participants to discuss their research and to answer questions. The group then identified and discussed specific research areas that would bring FHWA's research into the next 5 years, 10 years, 20 years, and beyond. This workshop summary report captures highlights from the workshop and summarizes the discussions that took place.

Part One

Presentations

Lighting the Infrastructure and the Environment: Progress and Issues in Roadway Lighting

Presenter: *Dr. Ron Gibbons*
Project Team: *Virginia Tech Transportation Institute*

Overview

Dr. Gibbons began his presentation with a brief introduction to the evolution of outdoor lighting over the years (Gibbons, 2014). He mentioned that two key developments have occurred, solid-state lighting and control systems. These developments have led to a lighting revolution primarily driven by the convergence of these two technologies. Dr. Gibbons presented research and findings from two projects conducted at the Virginia Tech Transportation Institute, "Spectral Effects of Light Sources" and "Adaptive Lighting." He then discussed potential areas of future visibility research.

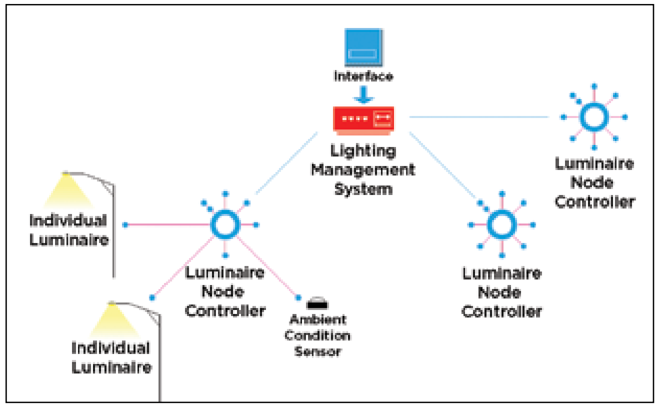

Figure 1. Control system topologies.

Summary

Solid-state lighting is a type of lighting that offers little flexibility or control; typically only on or off on a timer. Control systems offer more flexibility and control, take advantage of light-emitting diode (LED) technology, and create energy efficient, dimmable light-system management. Figure 1 presents a topology of how a control system works.

For Dr. Gibbons' first project, "Spectral Effects of Light Sources," he investigated the interaction of headlamps and overhead lighting, color recognition, and pedestrian object detection. Because the human visual system adapts well to blue light at night, and LEDs can now provide all colors of the spectrum, there is a potential to have a white light source, which could greatly increase visibility for night driving. Dr. Gibbons' research showed that lighting levels on roadways could be lowered and a shift in the broad spectrum to blue could decrease energy consumption, while maintaining or even increasing visibility.

For Dr. Gibbons' second project, "Adaptive Lighting," he investigated the ability to adapt roadway lighting systems to the needs of the environment. An adaptive luminaire system would reduce energy consumption and allow municipalities to install the systems where needed, reducing the costs associated with lamp replacement. To study whether adjusting the luminaire intensity affects crash rates, Dr. Gibbons' tested vehicles that were driven with various types of lighting systems, while accounting for traffic volume, weather, lighting conditions, and pedestrian usage. He then compared data involving 3,200 lane-km (2,000 lane-mi) of lighting with 23,000 crashes and identified that there are situations when lighting levels could be changed while maintaining safe levels of driving performance. Figure 2 provides the ratio of night-to-day crash rate and the corresponding horizontal luminance levels.

This analysis did not remove crashes attributed to impaired driving, and the number of crashes was stratified to determine whether lighting had a differential effect on impaired drivers compared with crashes involving pedestrians or objects.

Dr. Gibbons showed that the results were not significant and more lighting and crash data are needed for further investigation. He also described some potential areas for future research focusing on lighting systems and their effects on infrastructures, which are summarized as follows:

- Use geographic information system databases and collect information on roadway lighting, linking it to crashes on the same roadways.
- Determine the effects that lack of maintenance could have on detection and crash rates on the roadways and sidewalks. An increasing number of cities and municipalities are interested in looking at the effects of switching to LED systems, such as Anchorage, AK, and San Jose, CA. Both cities have instituted adaptable lighting systems (dimmable) and have maintained the same detection levels as when using a solid state system; however, cities still struggle to determine specifications for control system infrastructure (e.g., lens, expected life expectancy, cleaning, and maintenance). Data gathered in Boston, MA; Cambridge, MA; and Minneapolis, MN, measured light output from LED luminaries and showed how cleaning or changing lighting systems can affect the measureable output.
- Research how connected vehicles could be used to implement "lighting on demand" functionality for roadways, which would turn the lights on and off as a vehicle drives along the roadway.

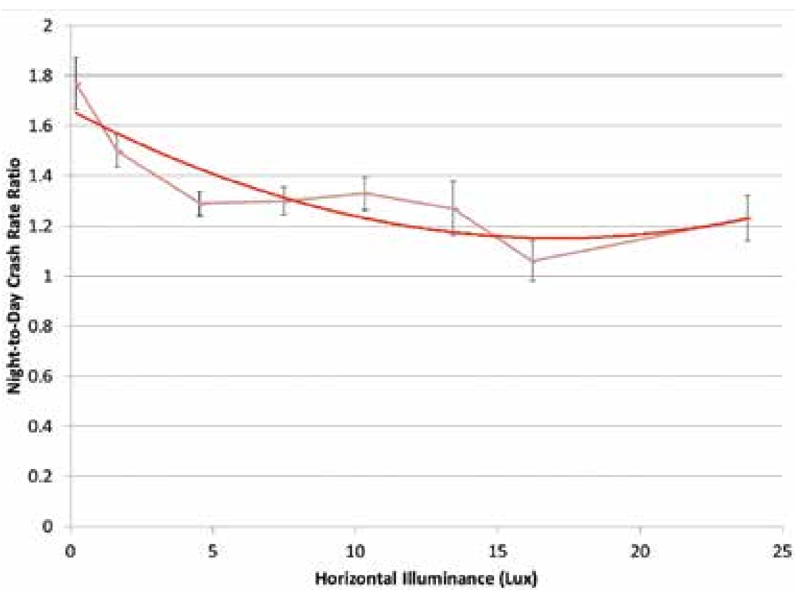

Figure 2. Driver crash rate and luminance.

Interaction of Vehicle Lighting with Traffic Control Devices (Retroreflectivity)

Presenter: *Dr. Paul Carlson*
Project Team: *Texas A&M Transportation Institute*

Overview

Dr. Carlson presented areas of completed and ongoing research related to retroreflectivity, pavement markings, and signage (Carlson, 2014). He also discussed topics for potential future research. These research areas included brightness and legibility of signage; placement, width, and materials used in pavement markings; and ways to expand on current performance values outlined in the *Manual on Uniform Traffic Control Devices* (MUTCD). In addition, Dr. Carlson provided examples where research could be expanded to establish retroreflectivity specifications and expected life cycles of signs and pavement markings.

Summary

Dr. Carlson explained that retroreflectivity is a passive technology and needs lighting to function properly. There have been many studies conducted that have investigated different aspects of signs as they pertain to retroreflectivity. For example, FHWA investigated sign brightness, retroreflectivity measurement biases, and the use of flashing signs; Minneapolis Department of Transportation (DOT) investigated fonts on guide signs; Florida DOT investigated sign lighting and the materials that should be used for roadway signs; researchers for *National Cooperative Highway Research Program (NCHRP) Synthesis 431: Practices to Manage Traffic Sign Retroreflectivity* explored and identified methods and best practices for traffic sign reflectivity that States are using to be in compliance with Federal regulations; American Association of State Highway and Transportation Officials' Subcommittee on Traffic Engineering conducted a survey to update NCHRP's reflectivity devices practices; and the Georgia Institute of Technology worked with Georgia DOT to assess light detection and ranging retroreflectivity.

Dr. Carlson also described previous pavement-markings research. FHWA published a study that tested pavement-marking performance in harsh environments (Alaska and Tennessee); NCHRP developed a new recommended procedure to test the retroreflectivity of glass beads, for which a specification is currently being developed; Missouri DOT investigated the safety of marking width, retroreflectivity, brightness, and placement; and the American Traffic Safety Services Association, in collaboration with FHWA, investigated the safety of pavement markings' retroreflectivity and pavement at night.

Dr. Carlson highlighted that the MUTCD established performance value sets for traffic devices. Researchers for NCHRP 05-20 are also working to expand and update the standards set in the MUTCD to describe how much light is needed to illuminate guide signs. To achieve this, the researchers worked to break down the complexity of the highway scene. By using images, they developed a program that would output a background complexity rating. Dr. Carlson explained that the complexity rate is calculated by using a static image, digitizing it to determine edge detection, and then assessing every pixel within the image. By using this complexity rating, the goal is to set standards and help determine when to light guide signs and how much light is needed.

Dr. Carlson also reviewed ongoing pavement-marking research. FHWA is working to develop standards to help select pavement markings for specific situations and environments; Illinois DOT is working to develop laboratory test methods to mimic the wear and tear of pavement markings in the field to accelerate performance testing for new technologies before installation on highways and roadways; and researchers for NCHRP 05-21 are investigating the safety and performance of raised pavement markings when paired with retroreflective pavement markings, in addition to determining additional benefits. Researchers for NCHRP Topic 46-13 are also studying rumble strips and profile markings to understand performance.

Dr. Carlson described several potential areas for research that range from establishing requirements for minimum retroreflectivity to investigating the usage and effect of digital signage along roadways. The following research areas were discussed:

- Establish requirements for minimum retroreflectivity. Researchers should specify a predicted life cycle of signs and identify when replacement would be necessary. The manufacturer's warranty period is not a good benchmark.
- Establish a link between the use and degree of retroreflectivity of signs and safety.
- Improve mobile measurements of retroreflectivity in many different ways. This could lead to variation among measurement methods. A better understanding is needed to develop test methods for these data-collection devices.
- Develop guidance relating to the brightness of luminaires for beacon and LED-enhanced signage and the amount of brightness used for these traffic control devices. The sign's message could be confused or lost if the luminosity is too bright (causing glare) or not bright enough (reducing visual acuity).
- Establish guidelines on appropriate usage of digital sign technology.
- Research how a driver internalizes the information presented on signage with different levels and types of retroreflectivity to operate the vehicle safely. This could be a multifaceted research project, beginning with when drivers read a sign, moving into comprehension and application of the information, and then looking at luminance curves to predict and define performance levels.

Vehicles of the Future and Visibility

Presenter: *Dr. Michel Ferreira*
Project Team: *University of Porto*

Overview

During his presentation, Dr. Ferreira described virtual windshields, vehicle-to-vehicle (V2V) connectivity, and new infrastructure technology (Ferreira, 2014). He explained that he has focused his research on the implications of virtual and electronic windshields on transportation infrastructure. These implications, as well as potential areas for future research, are described in the following section.

Summary

Dr. Ferreira noted that a driver's visibility is primarily affected by weather conditions and vehicle design (e.g., the windshield, dashboard, and pillars). Virtual windshields can be used to augment a driver's perception of the roadway. To achieve this, a computer uses the driver's perspective to overlay an image in their field of view and enhance the physical world as seen by the driver. Vehicles currently augment the driver's reality through the use of side- and rearview mirrors. That is, mirrors are used to augment the perception of what is going on behind the driver. These augmentations may improve the driver's visibility and awareness of his or her surrounding environment.

Dr. Ferreira explained that virtual windshields can be implemented through superimposed images on a head-up display (HUD) or other information display. Virtual environment technology includes parking assistance, cruise-control adaptability, lane-departure warning, and crash-avoidance systems. Vehicle manufacturers recently have begun removing the sideview mirrors and replacing them with cameras that display the side views on the centrally-mounted rearview mirror.

Dr. Ferreira highlighted how electronic windshields offer "see-through" visibility technology by using cameras to capture the environment and a computer to create digital content, which is displayed on the windshield. Dashboard information, global positioning system (GPS) navigation, and information from other vehicles can then be superimposed on the windshield view. For example, a truck could send its window view to the following vehicle so that driver can make a safe decision as to whether to try to pass the truck. Dr. Ferreira noted some potential issues with this technology. For instance, there could be delays in the image projection between vehicles, thereby increasing the risk of drivers making maneuver decisions with incorrect (i.e., late) information. Moreover, if one vehicle loses the ability to connect with other vehicles, then messages and information would not be shared, which may create blind spots for other vehicles.

Dr. Ferreira stated that there is a potential to use wireless technology and to synchronize a driver's smart phone with the vehicle's virtual windshield. The car would become a platform for a smart phone, but with a larger screen, and create a connected and an immersive ambient experience. He also stated that using wireless technology allows for more accurate information to be shared and increases the ability for V2V connectivity. In this scenario, every vehicle on the road would have a virtual traffic light that travels with the vehicle and would always be visible to the driver through the HUD. The interconnected vehicles on the road would monitor and sense area traffic when approaching an intersection and help govern traffic flow and safety.

Dr. Ferreira then described some potential areas for research in virtual windshields and visibility, as follows:

- Investigate the effect of augmented reality on a driver's decisionmaking performance. For example, "see-through" visibility technology could affect a driver's risk assessment, creating a false sense of safety.
- Identify the amount and placement of information on virtual windshields and HUDs. With increasing amounts of information available to drivers (e.g., GPS and dashboard information), there are questions as to how much information is too much information to be helpful and to facilitate safe vehicle operation.

A Unified Contrast Sensitivity Function-Based Framework for Edge Detection and Edge Visibility

Presenter: *Dr. Nicolas Hautière*
Project Team: *IFSTTAR*

Overview

Dr. Hautière presented his research on developing an edge-detection formula to aid in driver visibility during less-than-ideal conditions (e.g., fog and rain; Hautière, 2014). He developed this formula using photometrical visibility standards to analyze images without *a priori* information about target characteristics. He modeled the driver's perception and computed highway visibility through contrast estimation and measurement of the retroreflected luminance coefficient. Details about Dr. Hautière's research and areas for future research are described in the following section.

Summary

Researchers at the French Institute of Science and Technology for Transport, Development, and Networks (IFSTTAR) developed a mathematical formula to calculate edge detection and assist drivers by filling in the missing information from a driver's windshield view when visibility is poor. Three types of visibility are used to achieve this: (1) geometric visibility that relies on the geometry of the highway design and the presence of fixed and moving obstacles; (2) atmospheric visibility that relies on rain or fog intensity, granulometry, pavement properties, and vehicle velocity; and (3) photometric visibility that relies on lighting conditions and the color and photometry of objects. Figure 3 provides additional information related to these three types of visibility.

The research team at IFSTTAR was able to estimate the photometrical visibility through image analysis without any *a priori* information about target characteristics. Dr. Hautière explained that the driver's perception was modeled and highway visibility computed through contrast estimation and measurement of the retroreflected luminance coefficient. The research team validated the contrast model by using human subject testing. The subjects were able to reproduce better results than were the calculated results, making the model conservative and demonstrating the efficiency of this approach in real-world applications.

Dr. Hautière noted that this model could be used to assist the driver in fog conditions. The system would detect objects, apply the contrast model, and then represent the image on the HUD to improve the driver's reaction time through improved clarity and quality of visible cues. Dr. Hautière then discussed potential new areas for visibility research, as follows:

- Investigate how this technology could be used with "intelligent roadways" that contain smart cameras installed along the highway infrastructure to detect, characterize, and share visibility conditions with vehicles approaching the area. This cooperative system could be used to implement vehicle velocity control to match visibility conditions.
- Research how pedestrians would fit into the model. New driving simulations could be developed to account for this type of scenario and test the ability of the model to account for moving objects.

Figure 3. Roadway visibility concepts.

Human Visual System—Eye-Movement Analysis

Presenter: *Dr. Eileen Kowler*
Project Team: *Rutgers University*

Overview

Dr. Kowler presented research that focused on eye movement and the cognitive effort needed to make correct and efficient decisions (Kowler, 2014). Her research focused on human ability to complete computer-generated mazes of varying complexity by using different cognitive functions. The following section summarizes Dr. Kowler's discussion of how this applies to roadway visibility infrastructure and outlines other possible research areas to explore.

Summary

Dr. Kowler explained that saccadic eye movements (SEMs) are rapid jumps of the eye and that SEM scan patterns occur a couple of times per second. She noted that human cognition of the visual field decreases with eccentricity of the SEMs, that is, even when luminance cues are given, they are not always followed or recognized. Dr. Kowler mentioned that there is extensive research related to how people scan their visual field, retain, and make decisions based on this information.

Through human subject testing, Dr. Kowler showed that some individuals do not put forth the amount of effort needed to analyze the location of the luminance signal and the most efficient path to reach the location. For example, in a maze task, researchers asked participants to complete a randomly selected maze as fast as possible and to use the computer mouse to trace the path through the maze. Results showed that some participants used their eyes to explore the maze before moving the mouse; however, there were other participants who immediately started using the mouse instead of visually exploring the maze. Dr. Kowler's research indicated that the latter group of participants made more mistakes and took longer than did those who had visually explored the maze before tracing the path with the mouse. Figure 4 shows that although the subjects had ample opportunity to explore the maze, many did not.

Dr. Kowler suggested that the question of why people did not explore the entire maze relates to memory. The cost of exploration equals the amount of memory needed to retain the information, and some people do not use this cognitive tool. Dr. Kowler noted that human decisionmaking outweighs visibility and that adding a time pressure element to make a decision can make the task extremely difficult.

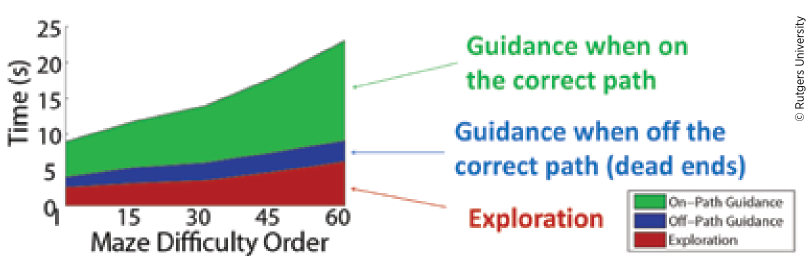

Figure 4. Eye movements navigating complex mazes.

Dr. Kowler discussed potential areas for visibility research as they relate to roadway infrastructure, as follows:

- Research individual differences in visual acuity and attention (e.g., attention deficit hyperactivity disorder). These differences could be confounding variables in visibility technology systems.
- Investigate how to measure when a person is seeing an object and when they actually process the information. In driving, there are SEMs because it is a dynamic environment with many tasks. Natural driving affects attention; when demands are low, there is better attention and vice versa.

Part Two

Discussion

Expert Panel Discussion

At the end of the first day, the presenters participated in a panel discussion and answered questions from the other workshop participants. The workshop participants directed general questions to all five presenters and also posed specific questions to individual presenters for their response. A summary of the panel discussion is outlined in the following sections.

Luminance and the Effect of Speed on Crash Rate

The panelists noted that when traveling on high-speed roads (e.g., interstate highways), the major visual task for the driver is to be aware of the vehicles ahead. More light is needed on slow-speed roads because of complexities (e.g., intersections and narrow and winding road curvature) associated with such roads. According to the panelists, older drivers tend to decrease the time they spend driving on unfamiliar or high-speed roads at night. In terms of visual capabilities, the panelists suggested that younger drivers have limited experience but have the best vision, whereas older drivers have the most experience but have impaired vision. The panelists mentioned that there is a gap in research in how changes in roadway infrastructure affect drivers familiar with the roadway and that there are various elements that could be included in the redesign to address this issue.

Driver Behavior and Visibility Effects from Glare

During the discussion, the panelists noted that there are hours of eye-glance data that need to be mined from the second Strategic Highway Research Program's naturalistic driving study. The panelists also highlighted that the California DOT (i.e., CALTRANS) is currently expanding its research on managing lanes. CALTRANS do not want to put up glare screens or glare walls and are investigating how much lighting could be installed to help drivers avoid looking at the glare of oncoming vehicles.

The panelists mentioned that researchers for a study conducted over a 3-year period in Finland collected data from drivers in high-speed and low-speed situations (Kallberg, 2014). Halfway through the experiment, the researchers installed reflector posts. In the high-speed situation, they observed no difference in driver behavior; however, in the low-speed situation, the reflectorization resulted in an increase in crash rates because drivers maintained a higher speed even though the road was complex. Researchers for this study theorized that reflector posts created a false sense of safety. This meant that drivers felt that they could keep their speeds high instead of decreasing them to appropriately and safely maneuver through the terrain.

Virtual Windshield and Driver Perception

The panelists spent part of the discussion focusing on virtual windshields and driver perception. They noted that the HUD reduces a driver's peripheral vision and acuity. Moreover, it can even create a hazard by inhibiting the driver's ability to refocus when the image being broadcast onto the screen brings his or her attention "in" instead of "out" (e.g., viewing the world outside of the vehicle). The panelists suggested that this may be worse than looking at the instrument cluster in a vehicle's dashboard. They also noted that the use of these virtual windshields is becoming more widely available. There is new technology moving toward interconnected vehicles and infrastructure that is leading the way for these windshields to project traffic signs and speed limits directly in the driver's immediate field of view. According to the panelists, this creates an increase in information workload and a new environment that the driver needs to adjust to. There is a significant need for human factors research and involvement to ensure high levels of safety with the emergence and adoption of these new technologies.

The panelists mentioned that there are individual differences when it comes to a person's ability to focus and respond to visual information. For example, when the driver has two sets of information (i.e., the projected and the real-world view), the human eye needs to choose which set of information to focus on. When there are two surfaces, including one that is transparent to the other view, people tend to choose to focus on the closest surface. In this scenario, that would be the information projected on the virtual windshield. Panelists noted the importance of a low contrast between surfaces when there is low illumination because there is less ability for the human eye to clearly focus on a specific view.

Gaps in Human Factors Visibility Research

The panelists also discussed gaps in human factors visibility research. They noted that the interaction between cars and connectivity is an important innovation, particularly in terms of driver perception. Vehicles will be able to send messages to other vehicles without any dependence on conditions. This is because intervehicle communication relies on established infrastructure, including lights, signs, markings, and sounds (e.g., horns). The panelists suggested that the loop needs to be closed between visibility devices and the capabilities of different drivers. More specifically, individual differences need to be studied and accounted for to ensure that these new visibility technologies can adapt to a wide variety of drivers. The panelists mentioned that researchers should study young, old, experienced, and novice drivers, and analyze their varying visibility requirements and mental capacity to understand the world around them.

According to the panelists, the infrastructure currently available encompasses the environment as a system of parts. These parts (e.g., street signs, traffic lights, and lane markings) are not "interconnected," but they work together to ensure safe highway and roadway travel. The panelists mentioned that one goal is to tighten up this system of parts by taking inputs from vehicles as part of future Intelligent Transportation System installations to form a cohesive system. During the discussion, the panelists also noted that researchers have previously conducted studies to analyze the effects of lighting on driver performance to model behaviors. The researchers focused on the direction of drivers' vision and which components of the visual system aided or inhibited a driver's visible acuity. When considering visibility and interconnectivity as a whole system, the panelists suggested that information silos need to be identified and broken down. The panelists put forward two specific questions that need to be answered: (1) does really good retroreflectivity mean that more or less lighting is needed; and (2) is it a better investment for municipalities to install dimmable systems that can be increased or decreased in energy consumption, rather than repainting pavement markings every 3–6 months?

The panelists agreed that there needs to be a better systematic approach to nighttime visibility. For example, the geometries for daytime visibility are different for pavement markings, retroreflectivity, signs, and raised pavement markings. The panelists suggested that research needs to be focused on identifying other performance metrics given that nighttime visibility is integrated. In addition, they agreed that nighttime visibility needs to be better defined, because current research is based on daytime conditions and assumptions. Although driver behavior, specifically in regard to speed, does not generally change between day and night driving, there are many other things that do change at night that are not documented in the MUTCD. The panelists highlighted that local and State governments are looking for objective performance data to justify new lighting infrastructure or to maintain existing surface infrastructure. At this time, it is not known if it is more cost-effective to spend money to install dimmable lighting or to spend money on maintaining existing pavement markings.

Smart Vehicle Technology

The panelists went on to discuss smart vehicle technology. With new "smarter" technology becoming increasingly more available (e.g., rear-visibility cameras, lane-keeping assist, and blind-spot monitoring), the panelists asked why accidents are still happening. They questioned what it is that the human element in this mix is failing to do and asked if onboard data recorders could be used to examine vehicle crashes after the fact and determine the fault. Panelists suggested that augmented systems could possibly help identify this missing link. They agreed that further research is needed to identify the shortfalls of these technologies and to find solutions to enhance their effect on safety.

Breakout Group Discussions

Potential Research Topics and Critical Questions

For the second half of this workshop, workshop participants split into two small groups to brainstorm and answer two different, but related, topics. The first session charged the groups to answer the questions, "What exploratory research do we need to do to get us to the future, and how do we coordinate across disciplines?" While the groups had the charge to consider exploratory and cross-disciplinary research, the discussion for the most part was on applied research with a narrower highway focus.

Session One: What exploratory research do we need to do to get us to the future, and how do we coordinate across disciplines?

- Roadside
  - *Develop MUTCD standards.* Research is crucial for amending and developing standards for the MUTCD to account for adaptive lighting and minimum retroreflectivity levels.
  - *Evaluate distractions.* There is a need to evaluate standards in terms of private land jurisdiction, brightness, and the amount of light from billboards allowed on the roadway and the distraction it may cause.
  - *Prioritize information.* There are no concrete data on what constitutes and defines "sign clutter." Standards are needed to prioritize the information displayed and to analyze this type of infrastructure on the roadway.
- Vehicles
  - *Prepare for the future.* Investigators need to conduct research to define and prepare for future technologies. Vehicle automation is on the horizon, and investigators need to identify research areas between partial automation and full automation.
  - *Implement monitoring.* There is a concern for the lack of implementation of monitoring technologies across passenger car fleets. The installation of black boxes in vehicles is a growing trend in the industry, which can provide information on such factors as speed, timing, and response to infrastructure.
  - *Streamline processes.* There are concerns about the number of different agencies that influence the approval of headlamp designs.
- Driver
  - *Investigate drivers.* With increasingly more safety technology on the market, there may be some unintended consequences. For example, drivers may be placing too much trust in these technologies and thus may neglect their own responsibilities. Additional research could explore the timespan needed for a driver to make a decision and assess risk.
  - *Research older drivers.* Research could investigate how driver performance changes with age and identify how visibility standards may help to evaluate whether a sign failed to warn older drivers as a result of visual or sign clutter.
- Cross-Cutting and Other Research Areas
  - *Coordinate disciplines.* There is related research in other areas (e.g., aviation and medicine) that relates directly to visibility, cognition, perception, and safe operation of vehicles. There must be coordination between the different disciplines and an emphasis on staying aware of new research.
  - *Identify pedestrians at night.* It is difficult for drivers to identify pedestrians and bicycles at nighttime. Infrared technologies, bio-motion, and lighting at night could be considered as options to identify heat, movement, and luminance of pedestrians and bicyclists.
  - *Focus research efforts.* The focus of future infrastructure needs should be made clear:

the focus should be on either the driver or the machine. Automation and new technologies are pushing highway research to shift focus from the driver to the vehicle. Because of this, investment in roadways may be directed to pavement markings, because sensor systems will be relying on this type of infrastructure. Researchers should still consider the driver when implementing virtual windshields and the amount of information (i.e., clutter) that is safe to present to the driver.

- *Study work zones.* Researchers need to focus more attention on the topic of visibility of work zones at night for drivers.
- *Influence behaviors.* The role of education in promoting safety and influencing behavior is an important factor to include in future research; however, it was noted by participants that much of this is outside of FHWA's jurisdiction.
- *Protect motorcyclists.* There is an increasing need for programs to address motorcycle fatalities. Potential solutions could include lighting systems embedded in helmets, technologies displayed on the windshield, and protective wear.

Session Two: Needed Applied Research and Next Steps

The second session focused on identifying and creating concrete next steps to move research toward addressing the ideas discussed in the first brainstorming session. These are outlined in the following sections.

1. **Adopt FHWA Visibility Vision Statement and Goals**
   Workshop participants said that FHWA has the potential to facilitate the focus of upcoming research by producing a vision statement. The direction set by this statement includes quantification of safety measurements and acceptance of new technology, and enables FHWA to react efficiently to new technology as it is introduced and available to the public. The group proposed a draft vision statement as a consensus of the different suggestions discussed. This vision statement communicates research objectives across infrastructure, vehicle, and user as follows:

> **FHWA Vision**
> "To provide the safest and most cost-effective visual environment for all users through full integration of infrastructure and technology."

2. **Create a Framework for FHWA's Visibility Research**
   The workshop participants proposed a framework (figure 5) in support of the aforementioned vision statement that identifies three main research components: infrastructure, vehicle, and user. Among the three components, workshop participants said that infrastructure is the component over which FHWA has the most influence. This framework correlates factors that can be controlled by researchers and practitioners and can be used as a reference to identify research needs.

   Figure 5 indicates consistent standards across infrastructure, vehicles, and users and consistent communications systems across infrastructure, vehicles, and users. Under this research framework, workshop participants suggested that projects in the next 5 years perform a benefit–cost analysis and assess the effect a study will have on vehicle-to-infrastructure and V2V communications.

3. **Develop a Clearinghouse of Research in Other Disciplines and Countries**
   Workshop participants suggested that a framework that brings together research and information is needed. The strategic program for visibility should include stakeholders and agencies that could contribute their respective research and help define uniform safety measurements and correlation factors. The workshop participants said that this research plan needs to be promoted to obtain inputs from stakeholders and to refine research needs based on

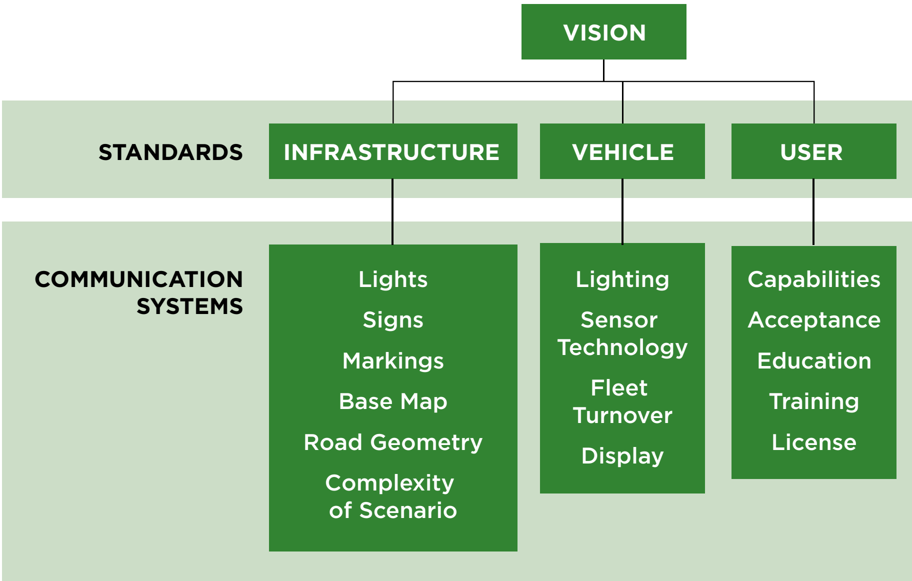

Figure 5. Proposed framework for visibility research.

visibility. Participants mentioned that a clearinghouse could be developed of relevant vision, human cognition and perception, and vehicle automation technology research. The workshop participants suggested the following list of key potential stakeholders:

- Transportation Research Board's Standing Committee on Visibility.
- American Association of State Highway and Transportation Officials.
- National Highway Traffic Safety Administration.
- Intelligent Transportation Systems Joint Program Office.
- FHWA Resource Center Innovative Finance Team.
- Academia.
- Automotive Industry (Alliance of Automobile Manufacturers and Japanese Automobile Standards Internationalization Center).
- Association for Unmanned Vehicle Systems International.

4. **Explore Driver, Pedestrian, and Night Simulation Training**
   Workshop participants discussed limitations in previous simulator research, specifically night simulation and pedestrian and driver interaction simulation. IFSTTAR has conducted some pedestrian and nighttime research, but workshop participants suggested that more is needed to understand driver behavior in the decision-making process, particularly when there is limited visual acuity, and to test new technologies.

5. **Identify Infrastructure Investments**
   During the discussion, workshop participants said that investment in new types of highway infrastructure may be needed over the next 20 years. They suggested that new infrastructure may be inclined toward automated driving and will incorporate vehicle and infrastructure sensors that do not rely on human vision but on machine–vision systems. Workshop participants mentioned that long-term investments should focus on providing the infrastructure elements and technology that will complement the entire integrated system.

6. **Investigate and Establish the Effectiveness of Retroreflectivity**
   Workshop participants discussed technologies that are already influenced by FHWA, including monitoring the driver and enhancing the visibility of the road through retroreflectivity

and lighting. Given that the effectiveness of retroreflectivity and lighting is not currently known, workshop participants said that more research needs to be conducted. This will help to determine whether there is a correlation between retroreflectivity, lighting, and a particular scenario of interest. Workshop participants suggested that FHWA could play a role as a facilitator and ensure roadways remain a focus of research.

7. **Update MUTCD and the *Highway Safety Manual***

   The final research area discussed by workshop participants related to how Congress mandates safety performance measures and crash-modification factors. These are used as predictive tools to guide expectations regarding reductions in crashes. Workshop participants mentioned that this requirement funds research based on the financial investment of the infrastructure. Participants highlighted that States have been charged with performance-based decisionmaking, whereas researchers use the available data to create these standards, even if they are not complete or of high quality. Workshop participants suggested that a next step would be to redefine and reestablish the minimum safety requirements set within the MUTCD and *Highway Safety Manual* using new technology specifications. They said that this type of research is an initial point, or a datum, for research over the next 5 years.

Appendices

Appendix A—Agenda

EAR Program Convening Workshop: Breakthroughs in Vision and Visibility for Highway Safety

Turner–Fairbank Highway Research Center, McLean, VA

Wednesday, August 13, 2014

1 p.m.	**Welcome, Introduction, EAR Program Overview** Monique Evans, *Federal Highway Administration* Michelle Arnold, *Federal Highway Administration* David Kuehn, *Federal Highway Administration*
1:15 p.m.	**Lighting the Infrastructure and the Environment: Progress and Issues in Roadway Lighting** Dr. Ron Gibbons, *Virginia Tech Transportation Institute*
1:45 p.m.	**Interaction of Vehicle Lighting with Traffic Control Devices (Retroreflectivity)** Dr. Paul Carlson, *Texas A&M Transportation Institute*
2:15 p.m.	**Vehicles of the Future and Visibility** Dr. Michel Ferreira, *University of Porto*
2:45 p.m.	**Break**
3 p.m.	**A Unified Contrast Sensitivity Function-Based Framework for Edge Detection and Edge Visibility** Dr. Nicolas Hautière, *IFSTTAR*
3:30 p.m.	**Human Visual System—Eye-Movement Analysis** Dr. Eileen Kowler, *Rutgers University*
4 p.m.	**Panel Discussion**
4:45 p.m.	**Adjourn**

Thursday, August 14, 2014

8 a.m.	**Day 1 Recap and Breakout Topic Introduction** Cathy Satterfield, *Federal Highway Administration*
8:15 a.m.	**Navigating the Transition Effectively—Breakout Groups** *Facilitated by Cathy Satterfield and Abdul Zineddin*
9:15 a.m.	**Present Findings to the Large Group**
9:45 a.m.	**Break**
10 a.m.	**Navigating the Transition Effectively—Breakout Groups** *Facilitated by Michelle Arnold and Joseph Cheung*
11 a.m.	**Present Findings to the Large Group**
11:30 a.m.	**Arens Photometric and Visibility Laboratory Visit**
12 p.m.	**Adjourn**

Appendix B—About the Presenters

Ron Gibbons

Dr. Ron Gibbons is the director of the Center for Infrastructure Based Safety Systems at the Virginia Tech Transportation Institute. He is also the Institute's lead lighting research scientist and is responsible for lighting- and visibility-associated research projects and projects that consider roadway safety as they relate to infrastructure. Dr. Gibbons is currently the principal investigator on multiple projects, including studies on the effect of lighting design on roadway safety, the effect of headlamp design on safety and wet night visibility, and the performance of alternative light sources in roadway lighting. Dr. Gibbons is the author of several published papers on roadway lighting, photometry, and target visibility. He is a past president of the Illuminating Engineering Society of North America. Gibbons obtained his doctorate degree from the University of Waterloo, Canada.

Paul Carlson

Dr. Paul Carlson is a research engineer at the Texas A&M Transportation Institute (TTI) and Division Head of the Operations and Design Division. Dr. Carlson leads TTI's Visibility Research Laboratory, located in TTI's new State Headquarters and Research Building. Dr. Carlson's primary areas of interest are traffic engineering, highway safety, vision science, traffic control devices, geometric design, and human factors. He has been a principal or co-principal investigator for numerous research studies, dealing with topics such as traffic-sign and pavement-marking retroreflectivity, highway safety, nighttime driver visibility needs, centerline and edge-line rumble strips, traffic-signal warrants, and operational effects of geometric design. Dr. Carlson holds a doctorate of philosophy in civil engineering from Texas A&M University and a master of science and bachelor of science degree, both in civil engineering, from The Pennsylvania State University.

Michel Ferreira

Dr. Michel Ferreira is a faculty member of the Department of Computer Science at the University of Porto, Portugal, and a researcher at the Porto Laboratory of the Instituto de Telecomunicações. He is a lead scientist in Intelligent Transportation Systems and principal investigator in several research projects. Dr. Ferreira currently leads the Geo-Networks group, and his main research interest is in the area of Intelligent Transportation Systems, in which he is especially interested in cooperative Intelligent Transportation Systems, where intervehicle communication plays an important role. Vehicular ad hoc networks, mobility simulation, and spatio-deductive databases are important topics in his current research. A major goal in his research is the efficient design of large-scale distributed systems that use infrastructure-less communication to self-organize, based on spatial reasoning. He received his undergraduate degree in computer science from the University of Porto in 1994, a master's degree in computer engineering from the University of Minho in 1996, and a doctorate degree in computer science from the University of Porto in 2002.

Nicolas Hautière

Dr. Nicolas Hautière is a researcher and program manager for IFSTTAR, the French Institute of Science and Technology for Transport, Development, and Networks. He received a master's degree in civil engineering from the National School of State Public Works, and a master's and doctorate degree in computer vision from the University Jean Monnet, Saint-Etienne, France, in 2002 and 2005, respectively. He received the habilitation to supervise research, HDR, in 2011 from the Université Paris-Est and the specialized master in political science and sustainable development in 2013 from Ecole des Ponts ParisTech. His research interests cover modelling of the meteorological phenomena reducing highway visibility, detection of adverse visibility conditions, and the estimation of visibility range. The applications range from road operation, including advanced driver assistance systems and video traffic sensors, to meteorological observation. Since September 2013, Dr. Hautière has been a Project Director at the Department Components and Systems, IFSTTAR, and leader of the French program "Route 5ème Génération."

Eileen Kowler

Dr. Eileen Kowler is Distinguished Professor of Psychology at Rutgers University and Associate Dean of the Graduate School. Her research includes the areas of perception, attention, and motor control. Dr. Kowler received her doctorate in psychology from the University of Maryland in 1978 and joined the psychology faculty at Rutgers in 1980 after postdoctoral work at New York University. She is a member of the graduate faculty of Biomedical Engineering and is on the Executive Committee of the Rutgers Center for Cognitive Science. She edited the reference work "Eye Movements and Their Role in Visual and Cognitive Processes" and served as section editor for "Behavioral Physiology and Visuomotor Control" for the journal *Vision Research* from 1995–2004. Dr. Kowler has served on the editorial board of the *Journal of Vision and Cognitive Brain Research*.

Appendix C—Attendees

Attendee	Organization
Roya Amjadi	Federal Highway Administration
Carl Andersen	Federal Highway Administration
Michelle Arnold	Federal Highway Administration
Stacy Balk	Leidos
Paul Carlson	Texas A&M Transportation Institute
Clayton Chen	Federal Highway Administration
Joseph Cheung	Federal Highway Administration
Ann Do	Federal Highway Administration
Monique Evans	Federal Highway Administration
Michel Ferreira	University of Porto
Brian Fouch	Federal Highway Administration
Ellie L. Francis	Ellie L. Francis, Ph.D., O.D.
Philip Garvey	Pennsylvania State University
Ron Gibbons	Virginia Tech Transportation Institute
Nicolas Hautière	French Institute of Science and Technology for Transport, Development, and Networks
Eileen Kowler	Rutgers University
David Kuehn	Federal Highway Administration
Alan Lewis	International Commission on Illumination
Paul Lutkevich	Parsons Brinckerhoff
Catherine McInnis	Volpe Center
George Merritt	Federal Highway Administration Resource Center
Cameron Miller	National Institute of Standards and Technology
Fred Owens	Franklin and Marshall College
Matthew Palmer	Virginia Tech Transportation Institute
William Perez	Leidos
Cathy Satterfield	Federal Highway Administration
Greg Schertz	Federal Highway Administration
Caroline Trueman	Federal Highway Administration
David Yang	Federal Highway Administration
Abdul Zineddin	Federal Highway Administration

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3. Ferreira, M. (2014, August). Vehicles of the future and visibility. Paper presented at the Exploratory Advanced Research Program Workshop, "Breakthroughs in Vision and Visibility for Highway Safety," McLean, VA.
4. Hautière, N. (2014, August). A unified contrast sensitivity function-based framework for edge detection and edge visibility. Presented at the Exploratory Advanced Research Program Workshop, "Breakthroughs in Vision and Visibility for Highway Safety," McLean, VA.
5. Kowler, E. (2014, August). Human visual system—eye-movement analysis. Presented at the Exploratory Advanced Research Program Workshop, "Breakthroughs in Vision and Visibility for Highway Safety," McLean, VA.
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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.

For more information, please visit the EAR Program Web site at http://www.fhwa.dot.gov/advancedresearch/.

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