CONNECTED VEHICLE/INFRASTRUCTURE UNIVERSITY TRANSPORTATION CENTER (CVI-UTC)

Connected Vehicle Applications for Adaptive Overhead Lighting (On-Demand Lighting)

MORGAN STATE UNIVERSITY
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University of Virginia
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Connected Vehicle Applications for Adaptive Overhead Lighting (On-demand Lighting)

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Submitted by:

Virginia Tech Transportation Institute
3500 Transportation Research Plaza
Blacksburg, VA 24061

Program Director:
Dr. Thomas Dingus
Program Director, Connected Vehicle/Infrastructure University Transportation Center
Director, Virginia Tech Transportation Institute
Professor, Department of Biomedical Engineering and Mechanics at Virginia Tech
tdingus@vtti.vt.edu
(540) 231–1501

Report Authors:
Ron Gibbons, Ph.D.
Director, Center for Infrastructure-Based Safety Systems
Virginia Tech Transportation Institute
rgibbons@vtti.vt.edu
(540) 231-1581

Matthew Palmer
Senior Research Associate
Center for Infrastructure-Based Safety Systems
Virginia Tech Transportation Institute
mpalmer@vtti.vt.edu
(540) 231-6279

Arash Jahangiri
Research Associate
Center for Infrastructure-Based Safety Systems
Virginia Tech Transportation Institute

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The mission statement of the Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC) is to conduct research that will advance surface transportation through the application of innovative research and using connected-vehicle and infrastructure technologies to improve safety, state of good repair, economic competitiveness, livable communities, and environmental sustainability.

The goals of the Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC) are:

- Increased understanding and awareness of transportation issues
- Improved body of knowledge
- Improved processes, techniques and skills in addressing transportation issues
- Enlarged pool of trained transportation professionals
- Greater adoption of new technology

Abstract

The Virginia Tech Transportation Institute (VTTI) has developed an on-demand roadway lighting system and has tested the system's effect on driver visual performance. On-demand roadway lighting can dramatically reduce energy usage while maintaining or increasing vehicle and pedestrian safety. The system developed by VTTI uses connected vehicle technology (CVT), wireless lighting controls, LED luminaires, and a stand-alone processor on the Virginia Smart Road to sense vehicles and turn on roadway lighting only when needed.

During this research project, the use of on-demand, or just-in-time, lighting was investigated with respect to assessing driver distraction, and to human factors, including a driver's ability to visually detect and recognize on-road objects and pedestrians. The developed on-demand lighting system described above utilized dedicated short range communication (DSRC), connected vehicle infrastructure (CVI), and centralized wireless lighting controls, and was used with VTTI-developed in-vehicle instrumentation and custom software. The software allowed the study of forward preview time in terms of forward lighting distance needed for drivers to detect roadside pedestrians and hazards.

Visual performance testing revealed a relationship between speed and the amount of forward lighting needed to detect pedestrians and hazards on the side of the roadway, and a small, but statistically insignificant, practical difference in visual performance between on-demand lighting and continuously-on lighting conditions. A survey of participant reactions indicated that the public generally accepts on-demand lighting and does not find it distracting as long as a minimum lighting condition is met. The survey also found that participants felt the system provided a safe driving environment. The main application for an on-demand lighting system would be on roadways with little traffic at night and higher accident rates, or higher conflict areas such as intersections, pedestrian crossings, and merge areas.

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Introduction

In an on-demand roadway lighting system, roadway lighting turns on when vehicles are present and turns off, saving energy, when vehicles are absent. On-demand lighting saves energy that would otherwise be wasted during times when vehicles or other users are not present. The ability to supply lighting only when it is needed will allow for larger areas of roadway lighting, or lighting in areas where energy costs would be otherwise prohibitive, thus enabling an increase in safety. Such a system requires solid-state lighting technology, which can be rapidly switched on and off, as well as connected vehicle technologies to sense the presence or absence of vehicles and trigger the lighting remotely.

The advent of solid-state lighting, in particular LED light sources, has made on-demand roadway lighting practical. Traditionally, most roadway lighting has used high pressure sodium (HPS) or metal halide (MH) high intensity discharge lamps, which require several minutes to warm up before reaching full light output. LED lighting, on the other hand, has a nearly instantaneous turn-on time. Now that LED lighting has become more efficient, it is an increasingly popular option for roadway lighting, and is present on many U.S. roadways.

Connected vehicle technology (CVT) encompasses new methods for vehicle-to-vehicle and vehicle-to-infrastructure communication, and has applications in mobility, safety, and for energy-savings. For CVT to be incorporated into an on-demand roadway lighting system, vehicles must wirelessly communicate their position, heading, and velocity to the lighting system, and the lighting system must respond appropriately to their presence, all without a noticeable delay to the driver.

This report describes the development of an on-demand lighting system and the human-subjects experimental testing of the system. The results of that experiment are detailed in the report and recommendations are provided for future research and development of on-demand roadway lighting.

Background

LEDs and On-demand Lighting

LED technologies have improved vastly in recent years, and are now one of the best options available for roadway, parking-garage, and parking-lot lighting. LEDs are robust and have a long life, reducing maintenance costs. Single LEDs are small and allow for excellent optical control, and are energized by dimmable and digital controller circuits called drivers. LEDs are also an energy-efficient lighting option, especially when dimmed to take advantage of the broad spectrum.

When used in combination with dimmers, already-efficient LED lighting can lead to even more energy savings. For example, if a lighting system could be dimmed to 50% brightness for at least 50% of the system burn time, a 25% energy savings would result. In 2001, one estimate [1] put the cost of outdoor lighting in the U.S. at $5.9 billion; a dimmable LED lighting system operating under the aforementioned conditions could save $1.49 billion.

Though it may provide huge potential savings, LED lighting also has drawbacks, including sensitivity to heat, reduced efficacy when driven at higher-than-optimum operating current, and high initial cost. Also, because individual LEDs are so small, they must be carefully combined with optics in a luminaire to prevent glare. LED lighting can lead to color identification-challenges, as phosphor-based broadband LEDs have less output than sunlight in the green spectrum. Despite these noted challenges, LED lighting is easily controlled, and is thus still the best possible candidate for an on-demand roadway lighting system.

Lighting Controls and Adaptive Lighting

Roadway lighting control systems are becoming more prevalent [2]. These control systems can allow wireless dimming and on-off control of individual luminaires. In this configuration, a base station communicates wirelessly and controls each luminaire through a transceiver, connected to the electronics, which controls the amount of light that each luminaire produces. The luminaire transceivers can form an ad-hoc network where commands are repeated from one luminaire to another, allowing low-power, low-cost wireless devices to access luminaires many kilometers from the home base. For LED luminaires, this allows dimming of the lighting from 100% output down to about 5–10% output depending upon the design.

Recently, guidelines [2] were published on how to design roadway lighting for adaptive lighting, which has the potential for dramatically reducing energy usage at night when traffic volumes are low, without decreasing the safety benefits. However, it is the capability to completely and quickly turn the LED luminaire on and off with these controls that enables on-demand lighting.

Connected Vehicle Technology (CVT)

Connected vehicle technology, where vehicles communicate their positions with each other and the infrastructure using any of a number of wireless technologies, is on the verge of an upswing.

CVT can be used in a number of applications, including signalized intersection crash-warning systems and adaptive-lighting systems. The overall goal of connected vehicle technologies is to improve traffic safety and efficiency, increase mobility, and reduce the environmental impact of transportation.

Applications for Connected Vehicle Technology

When used in conjunction with a signalized intersection, CVT can display in-vehicle information to drivers, including traffic-violation warnings, status displays of intersection signals, and alerts for oncoming emergency vehicles. To display such information to drivers, the intersection's signal phase and timing information must be conveyed to vehicles, and an algorithm must determine what to display.

Another CVT application is a forward-collision warning system, where the vehicle of interest receives position and speed data from all surrounding vehicles, identifies the forward vehicle, and compares the relative speeds of the vehicle of interest and forward vehicle to predict if a crash is likely to occur [3]. Additional applications include relaying weather data, traffic data, and cargo tracking [4], and providing information about the flow of traffic through work zones [5].

In the work-zone application, road-side equipment (RSE) developed for deployment at work zones provides travel time and start of congestion to on-board units (OBUs) in vehicles, allowing motorists to decide whether or not to take an alternate route.

Wireless Communication for CVT – Basic Safety Messages (BSM), Dedicated Short-range Communication (DSRC), and Cellular

For CVT to function, vehicle and infrastructure information must be communicated wirelessly. When comparing wireless technologies, bandwidth, latency, and range are all important considerations. The information packets from the vehicles, called basic safety messages (BSMs), are small, so bandwidth is less of a concern. BSMs contain many different variables that can be used singly or in combination for the application of interest. Each BSM has two parts: (a) part 1 includes vehicle position (latitude and longitude), vehicle heading, speed, acceleration, steering wheel angle, and vehicle size; and (b) part 2 includes variables that can be selected from a broad list, and which are based on event triggers [6]. For an adaptive lighting application, variables from BSM part 1, which can be broadcasted at a rate of about 10 times per second [7], are sufficient, and future references to BSM in this report are to BSM part 1.

Two main technologies exist for transmitting information from vehicles to other vehicles and to the roadway infrastructure: dedicated short-range communication (DSRC) and cellular technology. DSRC at 5.9 GHz is described as the most reliable, effective, and efficient communication method. It has a low latency of less than 100 ms and a range of less than 1,000 m [8, 9], and data can be broadcast from a vehicle to multiple locations. DSRC signals are sent from

OBUs in vehicles to RSE. DSRC is suitable for safety applications where warnings must be quickly passed to vehicles, but its limited range could be restrictive.

Cellular technology has a longer range than DSRC—4 to 6 km—but its end-to-end latency is 1.5 to 3.5 s. Cellular signals are broadcast by cell phones and received by base transceiver stations (BTS). Also, cellular communication has to be two-way—point to multi-point communication is not possible—and phone numbers must be known for communication to take place [8]. Fourth generation, long-term evolution (4G LTE) technology is promising, because it is reported to have a latency of about 30 ms [10].

On-demand Roadway Lighting System Development

Researchers and engineers at the Virginia Tech Transportation Institute (VTTI) designed an on-demand roadway lighting system on the Virginia Smart Road using a combination of available technology and resources along with new instrumentation. The system uses LED luminaires and CVT with DSRC wireless communication, and custom Smart Road Luminaires

On-demand Roadway Lighting – Design Considerations

General Architecture

An on-demand roadway lighting system would require a vehicle to pass its speed and heading information to an on-demand lighting processor, and the roadway lighting system to pass its status to the same processor. The processor would then decide which luminaires are in the vicinity of the vehicle, if they should be turned on or off depending on their status, and the location, speed, and heading of the vehicle. Then the processor would interface with a luminaire controller that would turn the luminaires on or off as needed. Figure 1 shows a schematic of such a system. Depending on the system, luminaire status could be fed directly to a processor, and/or the processor and lighting control system could be a single unit.

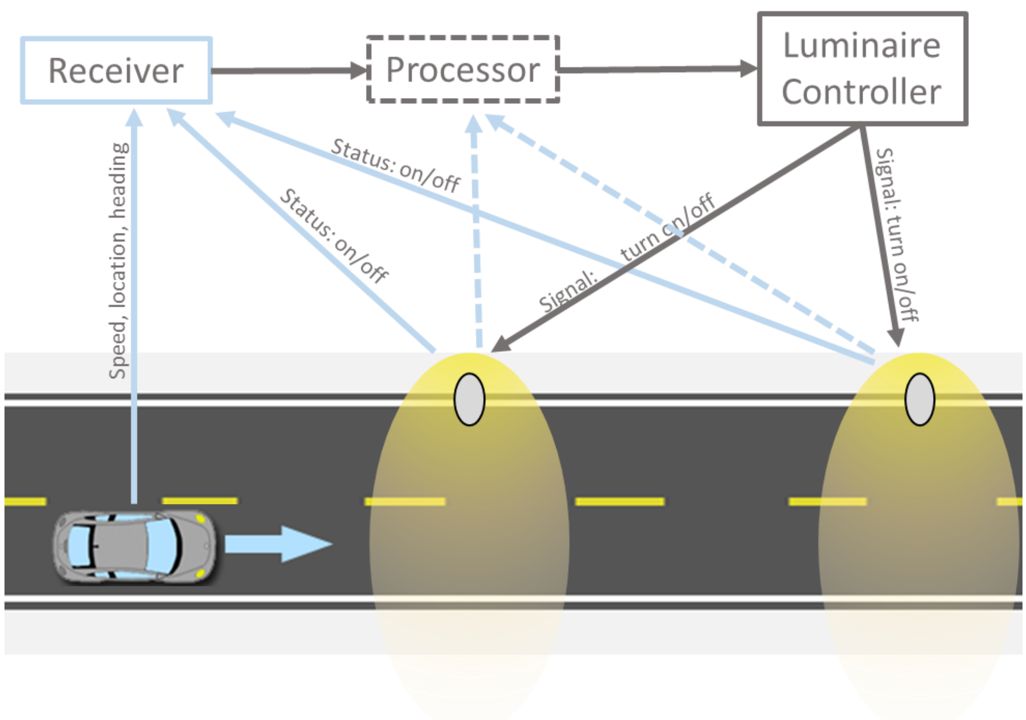

Figure 1. On-demand roadway lighting system.

Calculations for determining how far ahead of the vehicle to illuminate must take stopping sight distance and decision sight distance into consideration. Stopping sight distance is the distance drivers need to come to a complete stop, and decision sight distance is the distance drivers need to perform evasive maneuvers [11]. Calculations would take place inside either the processor or the luminaire controller.

Possible On-demand Lighting Systems

There are multiple communication pathways that could be used in an on-demand lighting system, five of which are described here. They either use cellular technology and a traffic-management center (TMC) or DSRC and a server as the on-demand lighting processor that interfaces with the luminaire controller.

Scenario 1. DSRC, DSRC RSE, TMC, Off-Site Controller, and Local Luminaire Controller

In this scenario, DSRC is the communication technology, with a TMC and a lighting system controller cloud in Alabama. As shown in Figure 2, vehicles in range of DSRC (~1000 m) send their status information, including location and speed, from their DSRC OBUs to the DSRC RSE. This information is then relayed to the TMC. The TMC has the location of luminaires and is able to identify which luminaires are required to be lit in front of the vehicle. This information is given to a remote controller cloud, which communicates with the local luminaire controller. Finally, the luminaire controller turns the required luminaires on. Table 1 shows the communication steps in order of occurrence.

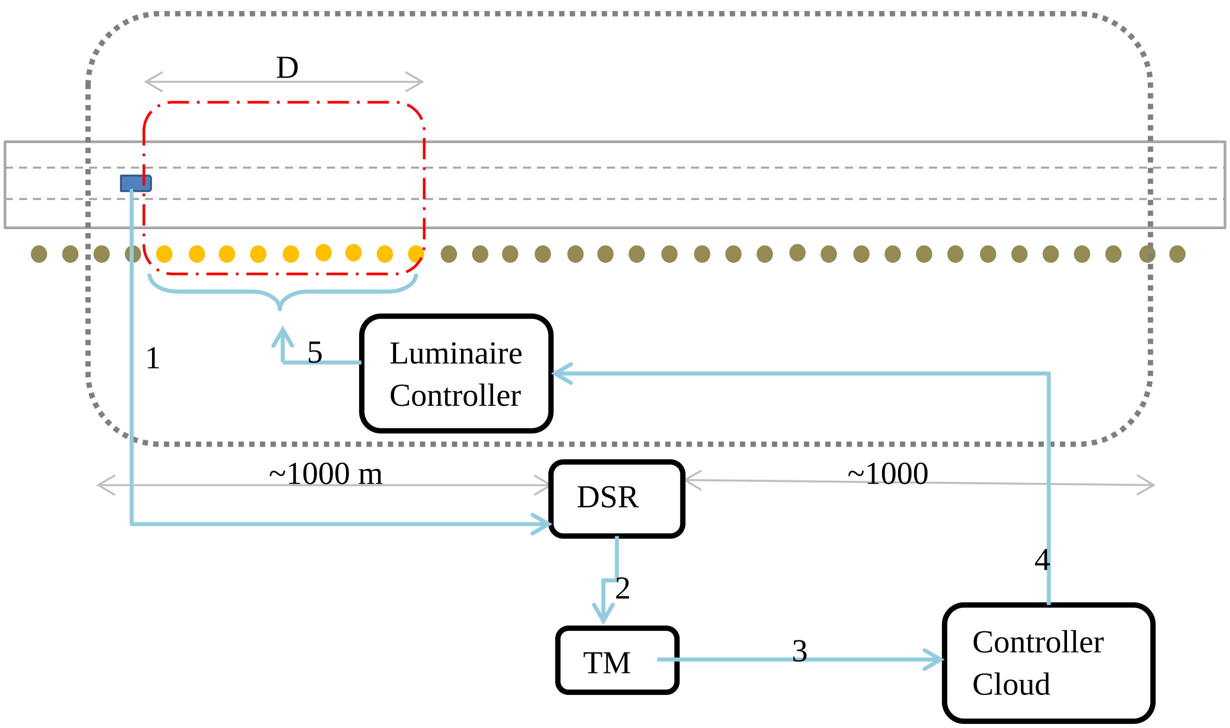

Figure 2. Communication pathways for scenario 1.

Table 1. Communication Steps for Scenario 1

Step	From	To	Means of Communication
1	Vehicle	DSRC RSE	DSRC
2	DSRC RSE	TMC	Wire
3	TMC	Controller in Alabama	Wire
4	Controller in Alabama	Luminaire controller	Internet
5	Luminaire controller	Luminaires	Wire

Scenario 2. Cellular, BTS, TMC, Off-site Controller, and Local Luminaire Controller

In this scenario, cellular is the communication technology, with a TMC and a lighting system controller cloud in Alabama. As shown in Figure 3, vehicles send their status information, including location and speed, from their cell phones to the BTS. This information is then relayed to the TMC. The TMC contains the location of luminaires, and is able to identify the luminaires to be lit in front of the vehicle. This information is given to the controller cloud in Alabama, which communicates with the luminaire controller. Finally, the luminaire controller turns on the required luminaires. Table 2 shows communication steps in order of occurrence.

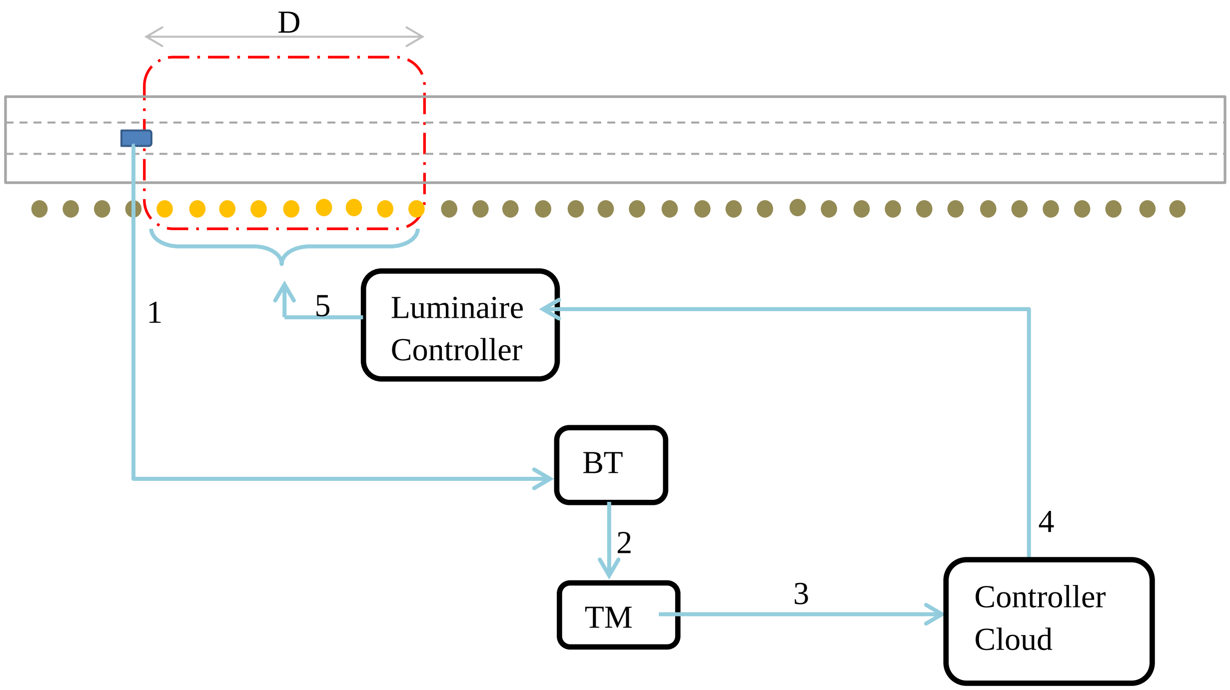

Figure 3. Communication pathways for scenario 2.

Table 2. Communication Steps for Scenario 2

Step	From	To	Means of Communication
1	Vehicle	BTS	Cellular
2	BTS	TMC	Cellular
3	TMC	Controller in Alabama	Wire
4	Controller in Alabama	Luminaire controller	Internet
5	Luminaire controller	Luminaires	Wire

Scenario 3: DSRC, RSE, TMC, and Local Luminaire Controller

This scenario uses DSRC and is similar to scenario 1, but does not include the off-site luminaire controller cloud in a remote location. Instead, the vehicle data is passed via DSRC to an RSE, then to a TMC, which identifies the luminaires that should be turned on, and then directly to a luminaire controller, which turns on the appropriate luminaires. Figure 4 is a diagram of the communication pathways, which are listed in Table 3.

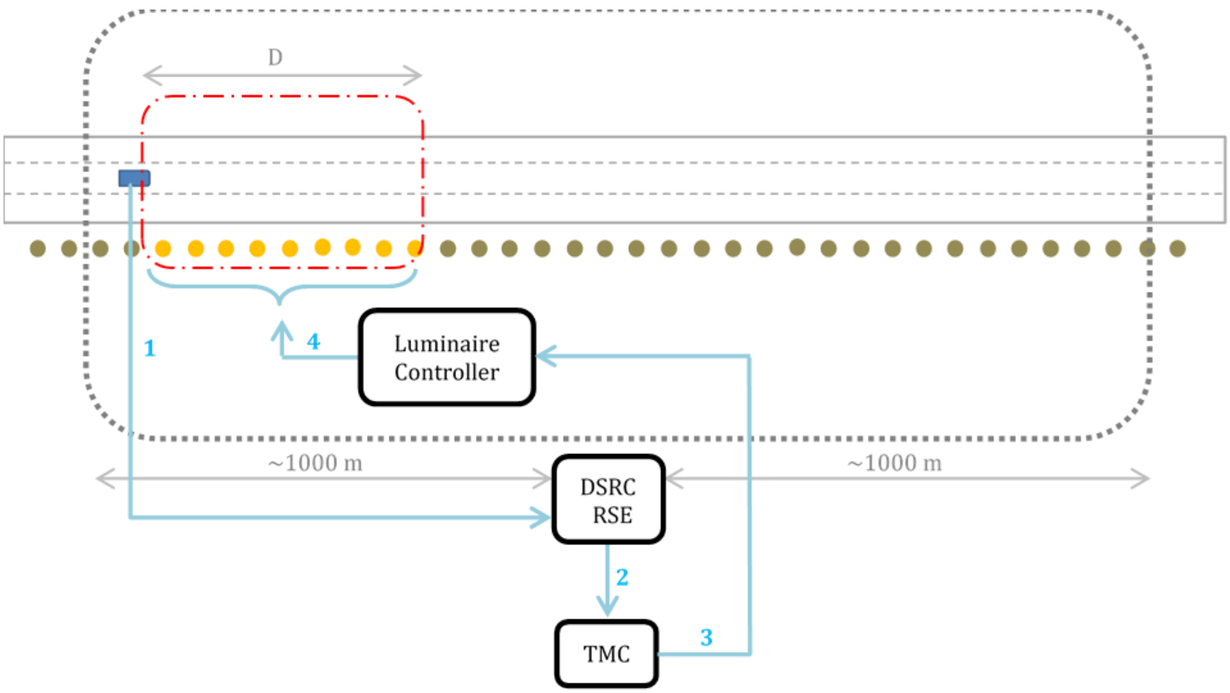

Figure 4. Communication pathways for scenario 3.

Table 3. Communication Steps for Scenario 3

Step	From	To	Means of Communication
1	Vehicle	BTS	Cellular
2	BTS	TMC	Cellular
3	TMC	Luminaire controller	Internet
4	Luminaire controller	Luminaires	Wire

Scenario 4: Cellular, BTS, TMC, and Local Luminaire Controller

This scenario also uses cellular communication, and is similar to scenario 2. But like scenario 3, it does not use an off-site controller cloud in Alabama. Instead, the vehicle data is passed via cellular to a BTS, then to a TMC, which identifies the luminaires that should be turned on, and then directly to a luminaire controller, which turns on the appropriate luminaires. Figure 5 is a diagram of the communication pathways, which are listed in Table 4.

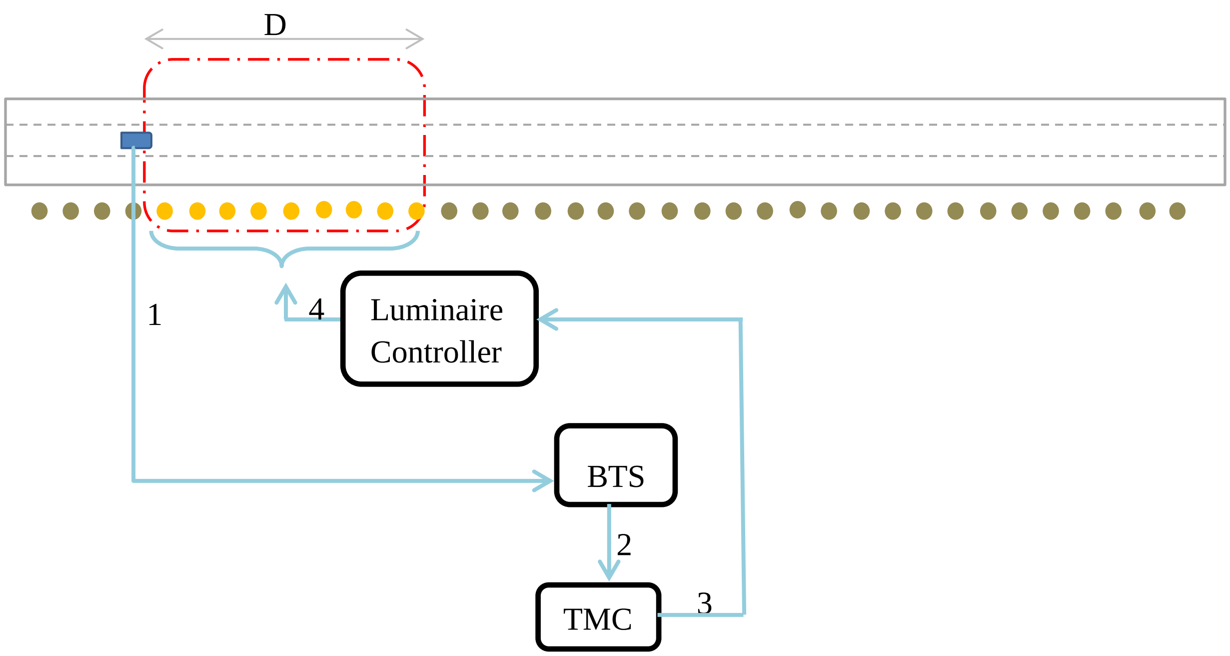

Figure 5. Communication pathways for scenario 4.

Table 4. Communication Steps for Scenario 4

Step	From	To	Means of Communication
1	Vehicle	BTS	Cellular
2	BTS	TMC	Cellular
3	TMC	Luminaire controller	Internet
4	Luminaire controller	Luminaires	Wire

Scenario 5: DSRC, RSE, and Local Luminaire Controller

This scenario is similar to scenario 3, but does not use a TMC. Instead, vehicle information is broadcast continuously by DSRC transmitters and received by RSEs. The RSEs pass the information to the local luminaire controller, which has the luminaire locations in memory and turns the appropriate luminaires on as needed. In this scenario, each DSRC RSE is associated with a luminaire controller along the road. Figure 6 is a diagram of the communication pathways for this scenario, which are listed in Table 5.

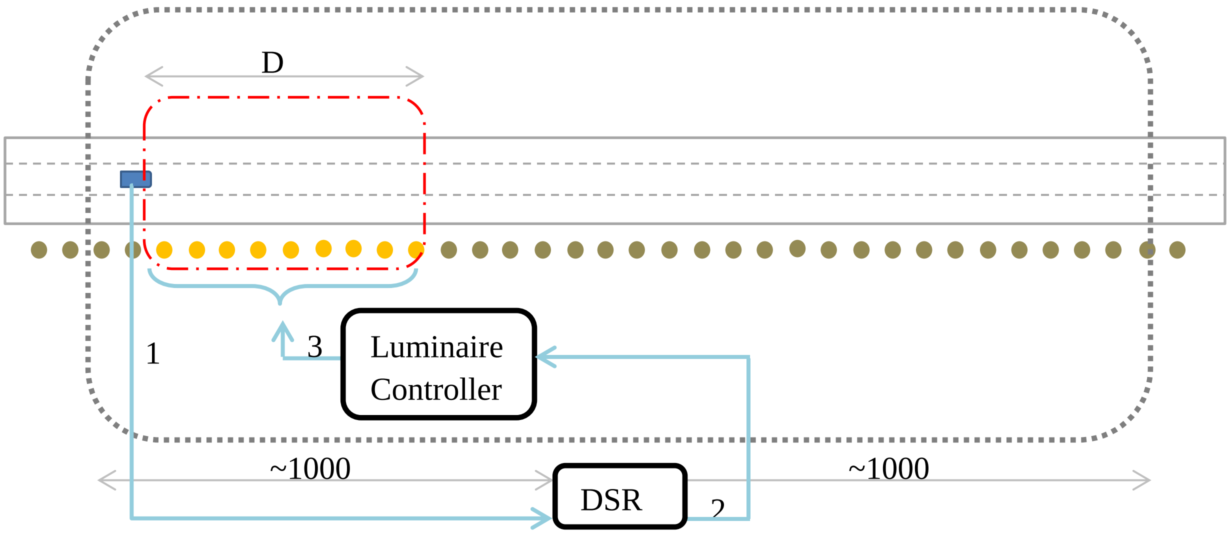

Figure 6. Communication pathways for scenario 5.

Table 5. Communication Steps for Scenario 5

Step	From	To	Means of Communication
1	Vehicle	DSRC RSE	DSRC
2	DSRC RSE	Luminaire controller	Wire
3	Luminaire controller	Luminaires	Wireless

Latencies of Scenarios

Depending on the scenario, three to five steps are required to send the information from one end (i.e., vehicles) to another end (i.e., luminaires). Each step represents a communication path between two parts. These steps are numbered for each scenario as shown in Figure 2 through Figure 6, but the numbers do not always correspond to the same step. For example, step 1 in scenario 1 represents the communication from the vehicles to the DSRC RSE, but in scenario 2, this step represents the communication from the vehicles to the BTS. To avoid confusion, the steps are coded alphabetically as shown in Table 6. The end-to-end latency—the summation of latencies associated with communication steps in the scenario of interest—is presented in Table 7. For example, L_1 of scenario 2 represents the latency associated with communication step 1 of that scenario, which is denoted by L_b.

Table 6. Relationship Between Two Different Coding Schemas for Communication Steps

Code	From	To	S 1	S 2	S 3	S 4	S 5
a	Vehicle	DSRC RSE	1		1		1
b	Vehicle	BTS		1		1	
c	DSRC RSE	TMC	2		2		
d	DSRC RSE	Luminaire controller					2
e	BTS	TMC		2		2	
f	TMC	Controller Cloud	3	3			
g	TMC	Luminaire controller			3	3	
h	Controller Cloud	Luminaire controller	4	4			
i	Luminaire controller	Luminaires	5	5	4	4	3

Table 7. End-to-end Latency Calculations

Scenario number	End-to-End Latency Calculation
1	$L_1 + L_2 + L_3 + L_4 + L_5 = L_a + L_c + L_f + L_h + L_i$
2	$L_1 + L_2 + L_3 + L_4 + L_5 = L_b + L_e + L_f + L_h + L_i$
3	$L_1 + L_2 + L_3 + L_4 = L_a + L_c + L_g + L_i$
4	$L_1 + L_2 + L_3 + L_4 = L_b + L_e + L_g + L_i$
5	$L_1 + L_2 + L_3 = L_a + L_d + L_i$

According to the literature (CAMP, 2005), communication steps involving DSRC are expected to have latency of less than 100 ms. This would result in the following.

$$L_a + L_c < 100 \qquad (1)$$
$$L_a + L_d < 100 \qquad (2)$$

Where,

$L_a =$ Latency of communication step a, ms
$L_c =$ Latency of communication step c, ms
$L_d =$ Latency of communication step d, ms

Latency of the system works with and is dependent upon the amount of forward visibility (or forward lighting) as well as vehicle speed to provide the vehicle driver time to react safely to road hazards or conflicts with other roadway users. Since this project was to explore the effect of on-demand lighting on driver visual performance, a latency was needed that would minimally impact the results of the other factors of the experiment. The shortest possible latency would be ideal but may not be practical., Given that human reaction time when anticipating an event is approximately 0.05 s, then any practical latency under 0.05 s would likely be unnoticed by vehicle drivers. Therefore, given the latency calculations, the cellular wireless approach was deemed to have too much latency.

Luminaire Identification Algorithm

In each scenario, the required luminaires must be turned on using a processor. This processor is located in TMC in scenarios 1 through 4 and in the DSRC RSE in scenario 5. Generally, two statuses exist: status 0, where there are no vehicles present and the luminaires are off, and status 1, where luminaires will be turned on. When motorists enter the area that requires lighting, the status is changed from 0 to 1, which involves a more dynamic process; this is when the luminaire identification algorithm is used.

Required Forward Lighting

The required lighting area in front of a vehicle is shown in Figure 7, in which parameter D, the length of the area to be illuminated ahead of the vehicle, is the factor to be determined. Regardless of how much lighting a vehicle's headlamps can provide, the length of the road in front of a vehicle that is visible to the driver, called sight distance, is an important design factor. This length needs to be sufficient for drivers under a variety of different conditions. In some cases they may need to be able to come to a complete stop (stopping sight distance). In other cases, they may need to make decisions to perform evasive maneuvers (decision sight distance). At night, vehicle headlamps and roadway luminaires must provide enough lighting out to the appropriate lengths for either of these conditions.

Figure 7. Required lighting area in front of a vehicle.

Stopping sight distance consists of two parts: brake reaction time and braking distance. Several factors, such as vehicle speed, roadway environment, and individual differences, influence the brake reaction time. Brake reaction time may be longer in complex situations. Braking distance is a function of the vehicle speed and deceleration rate, and deceleration rate depends on vehicle type and environmental factors. Stopping distance is formulated as follows [11].

$$d = 1.47Vt + 1.075\frac{V^2}{a} \quad (3)$$

Where,

$t =$ Brake reaction time, s
$V =$ Design speed, mph
$a =$ Deceleration rate, ft/s^2

For example, assuming the design speed is 60 mph, the stopping sight distance would be 566 ft. or 173 m.

In cases where drivers would prefer to perform maneuvers instead of stopping the vehicle, decision sight distance comes into play. Since this distance should be long enough to allow drivers sufficient time to make complex decisions for performing maneuvers at lower-than or up to the design speed, it is significantly greater than the stopping sight distance. A formulation similar to equation 3, but with some adjustments is used as follows [11].

$$d = 1.47Vt_1 + 1.075\frac{V^2}{a} \quad (4)$$

$$d = 1.47Vt_1 + 1.47Vt_2 \quad (5)$$

Where,

$t_1 =$ Pre-maneuver time, s
$V =$ Design speed, mph
$a =$ Deceleration rate, ft/s^2
$t_2 =$ Maneuver time, s

This formulation considers five different maneuver types: (A) stop on rural road, (B) stop on urban road, (C) speed/path/direction change on rural road, (D) speed/path/direction change on suburban road, and (E) speed/path/direction change on urban road. Note that a stop might be chosen as the best maneuver type (e.g. case A and B). Equation 4 is used for types A and B, and equation 5 is used for types C, D, and E [11].

It is important to keep in mind that other factors, such as the presence of grade or a truck as the vehicle of interest, can change both stopping sight and decision sight distances [11].

Algorithm Steps

Regardless of which wireless communication option is used to control the on-demand roadway lighting system, a processor of some sort must identify the luminaires to be turned on. The processor's output is either status 0, where there are no vehicles present and the luminaires are off, or status 1, where luminaires will be turned on. The processor must perform the following steps to determine whether to move from status 0 to status 1:

Step 1: Define the required lighting area based on stopping sight or decision sight distance.

Step 2: Obtain vehicle data, including position, speed, and heading via cellular or DSRC transmission.

Step 3: Obtain the positions of luminaires.

Step 4: Identify the closest luminaire to the vehicle.

Step 5: Identify if the vehicle is approaching or moving away from the closest luminaire.

Step 6: Identify the required lighting area from Step 1 with respect to the vehicle position and direction of travel from Steps 2 and 5.

Step 7: Identify the luminaries that are sufficient to light the required lighting area and inform the controller of those luminaire IDs.

Step 8: Turn on the required luminaires.

Designing for Oncoming Vehicles

In designing this system, one critical event that must be considered is two vehicles approaching each other on the roadway. There is a potential benefit to using the system, as the changing lighting may actually act as a notification of an approaching vehicle. The impact that changing lighting has on the driver has not been studied, and therefore, as part of this project, this triggering event will be investigated.

On-Demand Lighting as Implemented on the Virginia Smart Road

Lighting Infrastructure

A variety of luminaires are installed along about one mile of the 2.2-mile Virginia Smart Road, including two sets of LED luminaires of different correlated color temperatures (6,000 K and 3,500 K), either of which can be used for the on-demand roadway lighting system. The Smart Road's luminaires are controlled by a dedicated server.

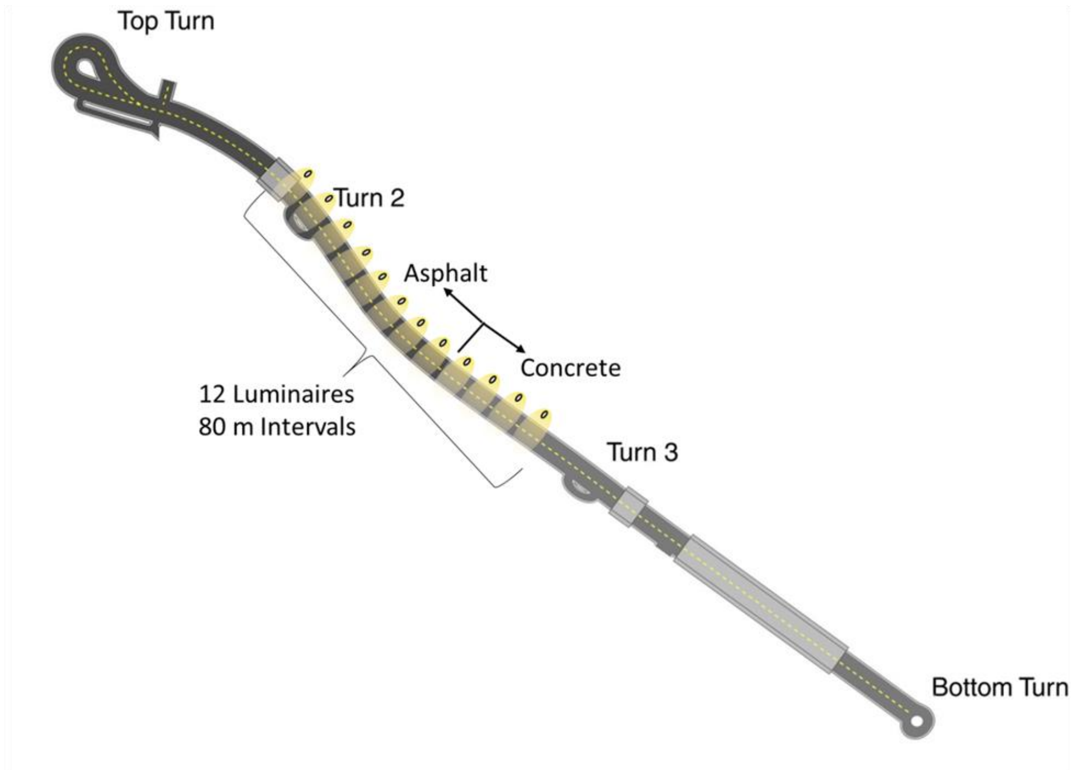

Figure 8. Virginia Smart Road diagram showing the lighted section of the Smart Road.

The spacing of the luminaires turned on and off in an on-demand lighting system is an important variable for human-factors research. The Smart Road lighting is flexible enough to allow luminaire spacing of 40, 60, 80 and 120 m. The on-demand lighting system was set up to use 80 m spacing and can use either the 6,000 K LED or the 3,500 K LED luminaires; for this study, all experiments were performed with the 3,500 K LED luminaires.

Lighting Controls

The Virginia Smart Road lighting installation includes advanced controls to provide for a large variety of lighting scenarios for research projects. There are two wireless control systems for each luminaire.

The primary controls used for on-demand lighting utilize a commercial-off-the-shelf (COTS) wireless addressable serial data link and custom luminaire control board (Figure 9). This wireless link allows central and ad-hoc networking. Each transceiver in the wireless network can act as a repeater, enabling relatively low power transceivers to communicate with the control room and server over miles of distance. The farthest luminaire on the Virginia Smart Road is 1.5 m from the control.

Figure 9. Custom, three luminaire control board and COTS wireless link.

The custom controller board provides power control to one of three luminaires mounted on each light pole on the Smart Road. The control boards allow each luminaire to be addressed individually, enabling independent control of each.

An additional wireless control system forms a supplementary network for dim level control for each luminaire. Each of the LED luminaires, and some of the HPS luminaires, on the Smart Road are equipped with dimmable light controllers that allow the LEDs to be dimmed from 100% to 0%, allowing further light level control. This network is controlled by a web application accessed either through a computer or a smart phone attached to the internet. Note that while this control system may be of interest in future on-demand lighting system studies, it was not included in the on-demand lighting system explored in this study.

Luminaire Control Program

The on-demand roadway lighting system receives DSRC vehicle transmissions of BSMs, including speed, location, and heading, using the RSEs. The RSEs then forward that data to the luminaire-control server, which runs a custom program. The program analyzes the BSM and determines a vehicle's location relative to the luminaires on the Smart Road. Researchers input the desired distance to be illuminated ahead of and behind the vehicle, and the program turns on the appropriate luminaires accordingly.

A calculation for stopping sight distance could be used to determine the distance in front of the vehicle to be illuminated, but the goal of this test system is to enable human-factors research of on-demand roadway lighting. So, instead, the on-demand lighting system allows researchers to vary the illumination distances depending on experimental conditions, and independent from vehicle speed. The system is not, however, totally independent of vehicle speed, because it must have a latency short enough that a driver does not notice a delay in the luminaire lighting. For the development of the lighting system in this study, vehicles traveled at 56 and 89 km/h (35 and 55 mph), common roadway speeds.

The luminaire-control software has input boxes for the experimenter to enter how far ahead of the vehicle to turn on the luminaires, and how far behind the vehicle to turn them off. It can also turn all selected luminaires on or off for control runs.

DSRC Infrastructure Technology

VTTI conducts ongoing connected vehicle research, and as such has a fleet of research vehicles equipped with DSRC. The Virginia Smart Road, located at VTTI, is also equipped with RSE, which receives vehicles' DSRC data. The on-demand roadway lighting system was designed and implemented using DSRC for vehicle detection. This system was also comprised of COTS wireless components and GPS components. The connected vehicle RSE equipment was attached to the same computer (server) to which the lighting control system is attached, enabling ease of integration.

Figure 10 shows two views of the on-demand roadway lighting system in operation. The main view is that of a test vehicle passing under a luminaire, and the view embedded in the upper left corner is the view of the luminaires in the "on" state behind the vehicle's seen in the side mirror.

Figure 10: On-demand lighting system in action with a test vehicle.

Two Vehicle Implementation

In the implementation used for this project, the software was programmed to illuminate the roadway around one test vehicle on demand, and then simulate the on-demand lighting from an oncoming vehicle by turning on luminaires according to a specified pattern (i.e., not on-demand and not driven by DSRC data from the second vehicle). The system was designed so a confederate researcher could drive the second vehicle, timing the approach to align with the period when the luminaires turn on and off, making it appear to the test vehicle driver as if the second vehicle were also triggering on-demand luminaire illumination. Figure 11 shows a diagram of how the simulation took place.

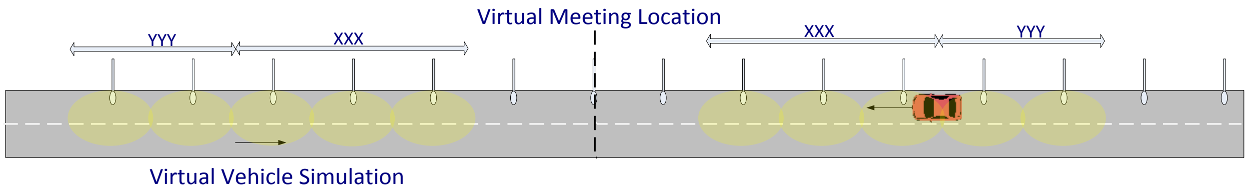

Figure 11. Oncoming vehicle simulation diagram. One set of luminaires driven by on-demand lighting (right), and the other set activated in a pattern simulating the presence of another vehicle (left).

Testing Driver Reactions to On-demand Roadway Lighting

Before major infrastructure changes can be tested and implemented on public roadways, driver reactions to those changes must be measured in a controlled environment. This section of the report describes a closed test bed experiment to test driver reactions to an on-demand roadway lighting system.

Experimental Design

The primary focus of the human factors experiment was to measure drivers' visual performance in relation to the on-demand lighting system. The function of roadway lighting is to increase safety by helping drivers see potential hazards on the road, and detect potential conflicts with pedestrians and other vulnerable users.

A mixed factors experiment was conducted to measure driver reactions to the on-demand roadway lighting system. Independent variables tested included speed, presence of an oncoming vehicle in the opposite lane, driver's age, how far ahead of the vehicle the overhead lighting illuminated, and how far behind the vehicle the lighting turned off (Table 8). Pedestrians and targets were also presented as independent variables in order to assess visual performance under the various on-demand lighting conditions. The pedestrian orientation and target orientation were also independent variables.

Since the Smart Road is a loop, a set of factors could be presented twice per lap. Twelve laps per participant were utilized to present the lighting ahead versus speed four times each (full factorial = 6 presentations). Sixteen participants were recruited, balancing age and gender. The remaining independent variables were presented as partial factorials with some weighting.

Dependent variables included detection and orientation-recognition distances for both pedestrian and target presentations to objectively measure visibility, driver perceptions of each lighting configuration, and the speed at which drivers felt comfortable driving given certain configurations.

Table 8. Independent Variables

Main Factor	Levels	Values	Treatment	Weighting *
Speed	2	56 and 89 km/h (35 and 55 mph)	Full Factorial	100%
Age	2	18–30 and 60 or older	Full Factorial	100%
Lighting Ahead of the Vehicle	3	160 m, 320 m ahead, Continuous Lighting	Full Factorial	100%
Lighting Behind the Vehicle	4	0 m, 80 m, 160 m behind and Continuous Lighting	Partial Factorial	100%**
Oncoming Vehicle	2	Yes or No	Partial Factorial	25%
Pedestrian	5	4 positions of decreasing vertical illuminance and none	Partial Factorial	80%
Target	5	4 positions of decreasing vertical illuminance and none	Partial Factorial	50%
Pedestrian Orientation	2	Facing toward the roadway or facing away	Partial Factorial	n/a***
Target Orientation	2	Tab facing toward the roadway or facing away	Partial Factorial	n/a***

* Weighting refers to the percent chance that the variable will be present versus not present across all trials and participants.

** 100% across all participants but not full factorial.

*** Roughly evenly split when present.

Independent Variables

Speed

The experiment was performed at 56 and 89 km/h (35 and 55 mph).

Oncoming Vehicle

Runs were completed with and without an oncoming vehicle. The oncoming vehicle created a glare condition, and was also timed so that it appeared to trigger the on-demand roadway lighting system from the opposite direction of the participant vehicle. There were two oncoming vehicle conditions: oncoming vehicle and no oncoming vehicle.

Age

Participants were divided into two groups to test age effects on visibility. Older participants were over 60 years of age and younger participants were between 18 and 30 years of age.

Lighting Ahead of the Vehicle

The roadway was illuminated ahead of the participant vehicle in three configurations: 160 m ahead of the vehicle, 320 m ahead of the vehicle, and all lighting on. These distances corresponded to two luminaires or four luminaires ahead of the vehicle, respectively.

For the final part of the experiment, participants were presented with two lighting configurations: 160 m ahead and 80 m behind, or 320 m ahead and 80 m behind. They were instructed to drive at a comfortable speed in order to assess whether the available lighting could control participant speeds.

Lighting Behind the Vehicle

The roadway was illuminated behind the participant vehicle in four configurations: 80 m behind the vehicle, 160 m behind the vehicle, all lighting on, and no lighting on. These configurations were applied randomly to limit the size of the experiment. Not all combinations were presented to the participants. When all lighting on was used as the lighting configuration forward of the vehicle, all luminaries remained lit behind the vehicle, as well. Similarly, when on-demand lighting was used as the lighting configuration forward of the vehicle, the lighting behind the vehicle was also on-demand. Luminaries remained lit behind the vehicle during the on-demand configuration until the vehicle was at either 0 m, directly under the luminaire; 80 m, one luminaire behind; or 160 m, two luminaries behind.

Pedestrian and Target Presentations

As stated earlier, confederate pedestrians and targets representing minimum sized road hazards were presented on the road shoulder to help assess the visual performance of the on-demand lighting. Trained researchers represented the pedestrians on the shoulder of the road.

One confederate pedestrian was presented randomly in one of four locations on the shoulder of the road during the experiment in order to characterize visual performance. The experiment was designed to use multiple locations for pedestrian presentation and no presentation (blanks) to minimize the chance of participants learning to anticipate a pedestrian in a specific location. Targets were also randomly presented in one of these four locations in an attempt to keep participants from learning to scan only for pedestrians.

The four locations were selected based on vertical illuminance values in an attempt to replicate real-world scenarios. The four locations were 1) Tower side – high vertical illuminance; 2) Tower side – low vertical illuminance; 3) Non-tower side – high vertical illuminance; and 4) Non-tower side – low vertical illuminance. *Tower side* refers to a position on the shoulder of the road directly under the luminaires. *Non-tower side* is the opposite shoulder. *High vertical illuminance* is a position in between luminaires poles to maximize vertical illuminance. *Low vertical illuminance* positions were directly under luminaires for a lower vertical illuminance.

Targets and pedestrians were positioned one half meter (18 in.) from the white line (fog line) on the shoulder of the road.

For each on-demand lighting condition, only one pedestrian at one location, one target at one location, a combination of one target and one pedestrian at two different locations, or a blank was presented; no other combinations were presented.

Pedestrian Orientation

Pedestrians were presented to participants in profile, either facing the roadway or facing away from the roadway.

Target Orientation

The targets utilized were 18 cm square with a 6x6 cm tab on one side for orientation (7 in. on one side with a 2.3 in. tab). Targets were presented facing the participant with the orientation tab facing left or right (i.e., facing either the roadway or away from the roadway).

Dependent Variables

Pedestrian Detection Distance

This variable is defined as the distance at which a participant was able to detect a pedestrian's presence. To measure detection distance, researchers instructed participants to say "person" when they first saw the pedestrian. At that moment, an in-vehicle experimenter pressed a button to flag that point in the data stream. GPS positions of the pedestrian locations were collected separately. Analysis was later performed to calculate the distance between the data stream GPS coordinates and the pedestrian GPS coordinates to determine the detection distance.

Target Detection Distance

The target detection distance was measured in the same way as the pedestrian detection distance, with the exception that participants were instructed to say "target" when they first saw a target. Figure 12 illustrates how target detection distance was measured.

Pedestrian Orientation Detection Distance

Participants were instructed to state which way the pedestrian was facing as soon as they were able to discern that. The researcher in the vehicle then pressed a button to flag the data. Again, post-processing analysis was used to calculate the distance between the GPS locations. That distance was the pedestrian orientation recognition distance.

Target Orientation Detection Distance

Target orientation detection distance was measured in the same way as pedestrian orientation distance. Figure 12 illustrates how target orientation recognition distance was measured.

Final Lap – Chosen Speed

For the final experimental lap, participants were presented with two lighting configurations and asked to drive at a comfortable speed up to 89 km/h (55 mph). For that lap, speed was the dependent variable.

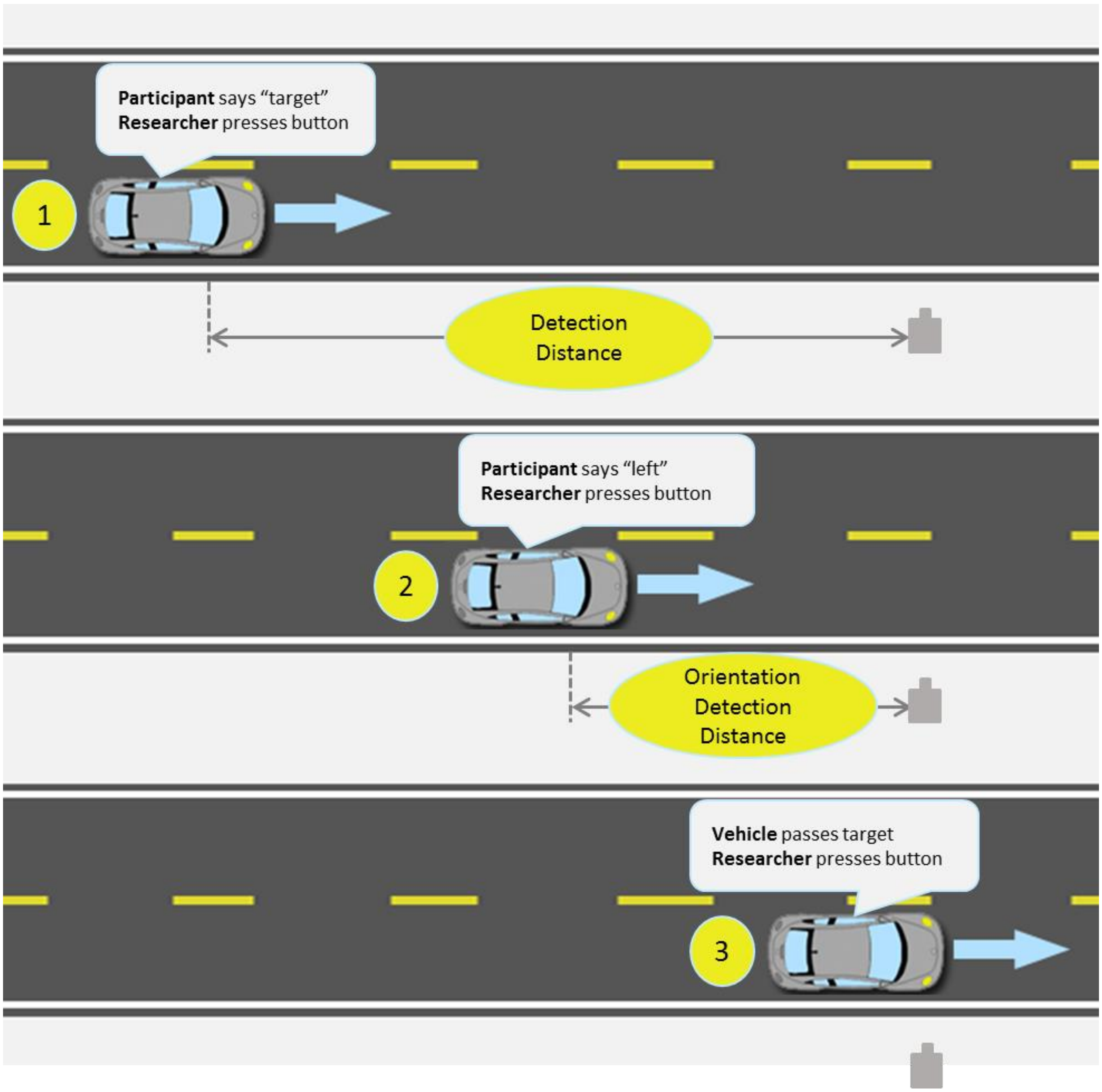

Figure 12. Illustration of pedestrian and target detection and orientation detection distance measurement.

Driver Questionnaire

After each pass through the portion of the Smart Road with the on-demand roadway lighting system, drivers were asked the following five questions regarding their perception of the lighting. They responded on a Likert-type scale of 1–5.

1. How much did the lighting in front of you help you? (1–5; 1 = not helpful, 5 = extremely helpful)

2. How much did the lighting in front of you distract you? (1–5; 1 = not distracting, 5 = extremely distracting)

3. How much did the lighting behind you help you? (1–5; 1 = not helpful, 5 = extremely helpful)

4. How much did the lighting behind you distract you? (1–5; 1 = not distracting, 5 = extremely distracting)

5. Was the oncoming lighting and vehicle distracting? (1–5; 1 = not distracting, 5 = extremely distracting)

6. Did you feel this lighting condition allowed you to drive safely at this speed? (1–5; 1 = Very Unsafe, 5 = Very Safe)

Facilities and Equipment

Confederate Pedestrian Clothing

To eliminate color as a variable, the pedestrians were dressed in uniformly gray garments.

Figure 13 shows the pedestrian in profile wearing the gray garments worn in the study. Pedestrians were not allowed to wear shoes with reflective materials or any other reflective clothing or accessories. The spectral reflectance of the gray clothing, calculated as a percentage relative to a diffuse white reflector, is shown in Figure 14. The integrals of the reflectance for the clothing, calculated between 360 and 800 nm using the trapezoid rule and weighted for the eye's spectral sensitivity, are listed in Table 9. These integrals give a direct comparison of how visible these colors would be in ideal conditions in bright light (photopic) and in very low light (scotopic).

Figure 13. A confederate pedestrian in profile with gray clothing on.

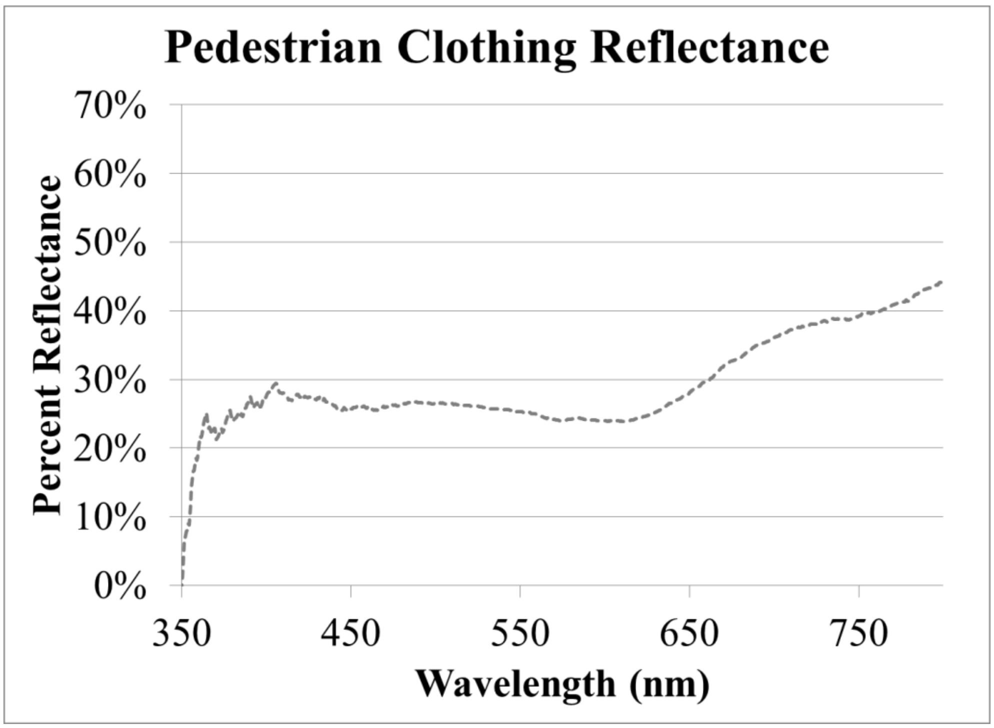

Figure 14. Pedestrian clothing reflectance.

Table 9. Integral of Pedestrian Clothing Reflectance

Clothing Color	**Gray**
Integral of reflectance (photopic)	26.9
Integral of reflectance (scotopic)	25.3

Targets

Matte gray paint was used on the targets to eliminate color as a variable. The targets were two-dimensional to remove the effect viewing angle has on a three-dimensional object, and they were designed to break if a participant ran over them. A photo of the gray target is shown in Figure 15, and the spectral reflectance is shown in Figure 16. The targets utilized were 18 cm square with a 6x6 cm tab on one side for orientation (7 in. on one side with a 2.3 in. tab). Targets were presented facing the participant with the orientation tab facing left or right (i.e., facing either the roadway or away from the roadway).

The integral of the reflectance for the gray target, calculated between 360 and 800 nm using the trapezoid rule and weighted for the eye's spectral sensitivity, are listed in Table 10.

Figure 15. Target.

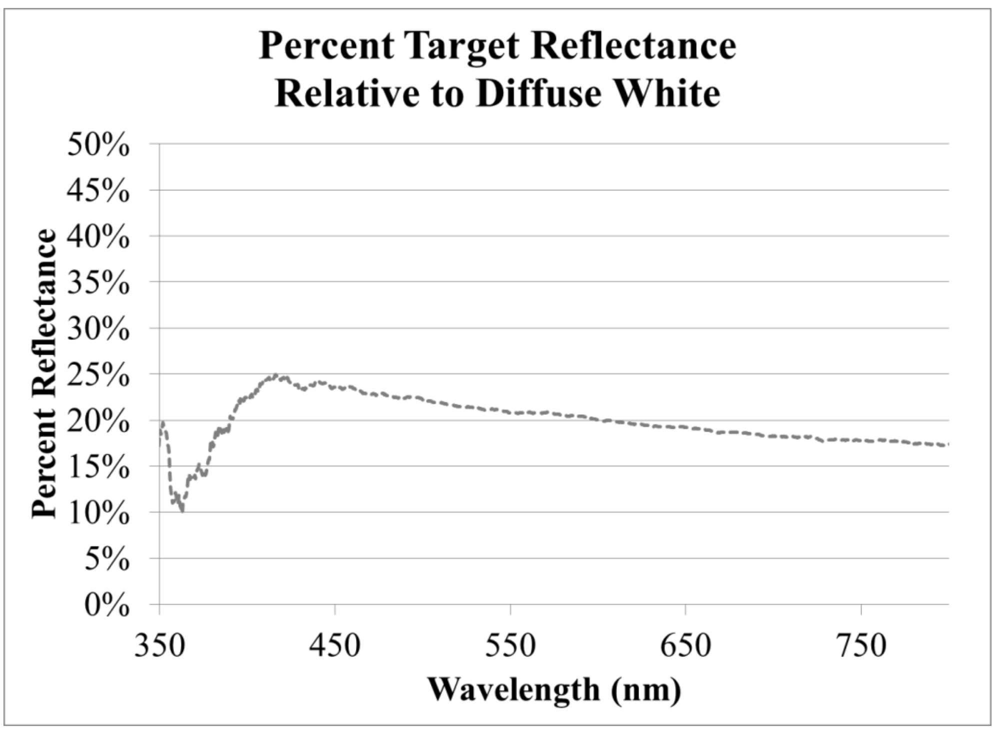

Figure 16. Target reflectance relative to diffuse white.

Table 10. Integral of Target Reflectance

Target Color	Gray
Integral of reflectance (photopic)	22.3
Integral of reflectance (scotopic)	21.5

Target and Pedestrian Vertical Illuminance

Each of the four positions for presentation of a pedestrian or target had different lighting conditions. Since these conditions were not changed independently from the positions, these conditions were covariate. To characterize the lighting conditions, all of the luminaires were turned on and the vertical and horizontal illuminances were measured.

Illuminance is the measure of the amount of light falling on a flat plane. Horizontal illuminance is the measure of light falling on a horizontal plane, in this case the road surface. Vertical illuminance is the measure of lighting falling on a plane perpendicular to the horizontal plane. A Minolta T-10 illuminance meter was used to make the measurements. The horizontal measurements were obtained by placing the meter on the shoulder of the road in the exact location of presentation. The vertical illuminance was measured in two planes: one perpendicular to direction of travel of the lane adjacent to the shoulder facing the direction of travel, and one facing the opposite direction. These two vertical illuminances were averaged to reduce the number of factors in the experiment.

The vertical illuminances for the pedestrian presentations were measured at a height of 1.5 m, the standard for face recognition. The vertical illuminances for the targets were measured at height of approximately 0.1 m, at the center of the target.

Table 11. Pedestrian Illuminances

Locations	Side	Vertical Illuminance, lx	Horizontal Illuminance, lx	Vert./Hor.
Top	Tower	1.69	4.63	0.36
Top	Non-Tower	2.66	7.44	0.36
Bottom	Tower	2.84	3.06	0.93
Bottom	Non-Tower	3.79	3.92	0.97

Table 12. Target Illuminances

Locations	Side	Vertical Illuminance, lx	Horizontal Illuminance, lx	Vert./Hor.
Top	Tower	1.40	4.63	0.30
Top	Non-Tower	2.58	7.44	0.35
Bottom	Tower	2.67	3.06	0.87
Bottom	Non-Tower	3.56	3.92	0.91

Virginia Smart Road

The experiment was conducted on the Virginia Smart Road, located in Blacksburg, VA, as previously shown in Figure 8.

Vehicles and Instrumentation

Two 2006 Cadillac STS sedans were utilized for the experiments. These vehicles were similarly equipped and both utilized high-intensity discharge (HID) low beam headlamps. The low beam headlamps were used in this experiment during all conditions.

On-Demand Roadway Lighting System

The on-demand roadway lighting system described previously in this report was used for this experiment.

Procedure

Demographics

Sixteen participants were recruited for the experiment. The participants were evenly distributed among age groups and gender. The age groups recruited were between 18–30 years for the younger participants and 60 years and up for the older participants. Average ages for the recruited participants are shown in Table 13. Of the 16 participants recruited for the experiments, data from 15 were usable. Experimental data from one older male was not useable, but his survey responses were still usable and were included. All participants passed the visual screening.

Table 13. Demographics of Recruited Participants

Demographic	Age	Visual Acuity Both Eyes	Low Contrast Visual Acuity	Acuity with Mesopic Filter	Useful Field of View (UFOV)
Older	65.4	20/21.8	20/33.1	20/32.6	2.0
Younger	24.0	20/17.5	20/19.1	20/26.5	1.0

Telephone Screening

After participants meeting age and gender requirements were identified, a research assistant called them to ask if they were interested in participating in the study, to gain consent for a screening, and to perform the screening. Participants found to be eligible via telephone screening were scheduled to come to VTTI for vision screening.

In-person Screening

When participants arrived at VTTI, a researcher obtained written informed consent, had participants fill out a W9 tax form and health questionnaire, and administered the following vision tests: useful field of view (UFOV), visual acuity, low-contrast visual acuity, mesopic visual acuity, and color vision.

Health Questionnaire

Participants filled out a health questionnaire with questions regarding basic demographic information, health concerns in the last 24 hours, and their comfort with driving at night. Those with serious health concerns or a fear of driving at night were excluded.

Useful Field of View (UFOV)

Participants used a computer program that tested their UFOV. Scores ranged from zero to five; those with a score of three and over were excluded.

Visual Acuity

Participants' binocular visual acuity was measured using a Snellen Early Treatment Diabetic Retinopathy Study (ETDRS) acuity chart. Those with vision worse than 20/40 were excluded.

Low-contrast Visual Acuity

Contrast plays a major role in differentiating between objects and their backgrounds. The contrast sensitivity test used an illuminator with a Snellen eye chart with 25% contrast. Participants' binocular and monocular performance was measured. No participants were excluded based on low-contrast visual acuity.

Mesopic Visual Acuity

A Snellen visual acuity exam was repeated in mesopic lighting conditions. No participants were excluded based on mesopic visual acuity.

Color Vision

Participant's color vision was tested using an Ishihara Color Vision exam. Those without color vision were excluded.

Experimental Sessions

Those eligible for the experiment after completing the vision and health screening were asked to come to experimental sessions. Two participants completed the experiment during each session. Before each session, participants gave their informed consent, verified they were healthy enough to participate, and showed the experimenter their valid driver's license. The vision testing was performed only once during participant screening.

Data Collection

In-Vehicle: After participants completed the consent and testing portion of the session, experimenters escorted them to the test vehicles, where they were familiarized with the vehicle controls. They then drove the vehicles to the Smart Road and drove a practice lap followed by 13 experimental laps.

During the first 12 laps of the experiment, the two participants drove through the test section of the road one at a time, pausing at one of the turnarounds while the other vehicle completed its lap. The participant driving the test lap would state whether they saw a target or pedestrian and what color they saw, and the researcher recorded the detection with a button press. The researcher also ensured that the participant was driving safely and at the correct speed. After the participant passed through the section of the Smart Road with the on-demand roadway lighting system, they paused and responded to the questions regarding their perception of the lighting.

For the 13th lap, participants were not asked to detect targets or pedestrians, but were asked to drive at a speed they felt comfortable, up to 55 mph, given the lighting configuration.

On-road: Pedestrians positioned themselves and/or the targets alongside the road according to the protocol for that session. The test vehicles would only pass through the test portion of the road once the on-road experimenters confirmed the targets and pedestrians were in place, and that the on-demand roadway lighting system was set correctly for that experimental run.

Oncoming Vehicle: A confederate researcher drove the oncoming vehicle and matched speed with the on-demand roadway lighting system's illumination to simulate an oncoming vehicle triggering the lighting system. When the experimental run did not call for the oncoming vehicle, it was parked next to a particular light pole. When the lights on the pole illuminated, the confederate driver knew to proceed.

Compensation

After completing the experimental laps, the participants exited the Smart Road and were compensated for their time.

Vehicle Instrumentation

The system was designed to operate with two nearly identical vehicles. This enabled one participant to perform an experimental run through the section of the Smart Road with on-demand roadway lighting while the other participant turned around at the top and bottom of the Smart Road and responded to a questionnaire.

Both vehicles were instrumented with DSRC, which was part of the on-demand system, and a VTTI data acquisition system (DAS), which measured vehicle location, speed and heading via GPS and accelerations; recorded forward video and in-vehicle video; and allowed a researcher to press a button, marking the data stream (Figure 17). Researchers marked events of interest in the data stream in order to identify the points in time when participants were able to detect and identify the orientation of both the pedestrians and targets.

These data points and the recorded video were later utilized to, from GPS coordinates, locate the vehicle at the specific times participants indicated detection or orientation of the targets/pedestrians. The vehicle GPS coordinates were then used with the target/pedestrian GPS coordinates to calculate the distance between the participants and the targets/pedestrians.

Figure 17. VTTI in-car data acquisition system (DAS), which measures a large number of variables and records video from four in-vehicle cameras.

Data Analysis

There were some challenges associated with reducing the data due to a hardware failure in one vehicle, but the team was able to process the video data to get the timing of pedestrian and target detections in most cases.

The data from the Smart Road testing was not recoverable for one male in the older age group. This resulted in the loss of 6.25% of the visual performance data and unbalanced the factors. Any questionable data from the remaining participants was dropped from the analysis; this data was less than 2% of the total remaining pedestrian detection measurements. Of these remaining 255 pedestrian presentation observations made, 251 were valid detections (not misses). In this analysis, participant number and age were nested, and were used as the error term in the hypothesis testing.

The data collected consisted of the vehicle driver's GPS coordinates at the time they stated that a pedestrian or target was detected or its orientation was detected. If a false statement was made, this was counted as a miss. The GPS coordinates of the presentations were measured after completion of the human factors experiment. The distance between the vehicle driver and the pedestrian or target location was then calculated in meters for analysis.

Analyses of variances (ANOVAs) were performed using commercial statistical software packages and a 95% confidence level was selected, as is typical for most human factors analyses.

There were not enough degrees of freedom to analyze the data with an ANOVA if the class "lighting behind the vehicle" was included, even when attempted with mixed factor modeling. It is believed this is due to the partial factorial presentation of "lighting behind the vehicle" and due to the loss of one participant, which unbalanced gender and age. Therefore, the covariance of the lighting behind the vehicle was instead analyzed in the ANOVAs. This was done by assigning 1,120 m to the condition of continuous backlighting. This length (1,120 m) is equivalent to the entire length of the lighted section. The statistical software then calculated the mean of the backlighting associated with the mean response for each factor or factor interaction.

The results for pedestrian detection distance, pedestrian orientation distance, pedestrian orientation misses, target detection misses and target detection distance were all analyzed independently. To analyze the results of misses with respect to successful detections, a dependent variable was created where a detection = 0 and a miss = 1. This was substituted into the statistical program in place of the detection distance and an ANOVA recalculated.

Results

Pedestrian Detection Distance Results

The hypothesis test results for pedestrian detection distance are shown in Table 14. As the table shows, the only statistically significant correlation with the detection distance is the pedestrian location. Of note, the relationship between detection distance and on-demand forward lighting (light) is not statistically significant, which seems to indicate that implementation of on-demand lighting will not significantly affect visibility. Speed and Speed*light (forward lighting) have a p factor of 0.12 and 0.09, indicating that these results were not statistically significant to the 95th percentile in this study.

Table 14. Hypothesis Test Results

Factor or Interaction	F Value	Pr > F	DF	Type III SS	Mean Square
Pedestrian Location (Ped. Loc.)	7.16	0.001	3.00	37442.28	12480.76
Speed*light	55.33	0.09	2.00	1865.00	932.50
Speed	2.80	0.12	1.00	2208.24	2208.24
light*Ped. Loc.	4.27	0.20	4.00	16742.11	4185.53
age*Ped. Loc.	1.56	0.22	3.00	8162.95	2720.98
age*glare	1.89	0.24	1.00	1837.18	1837.18
age*Speed*Ped. Loc.	6.99	0.26	2.00	5837.95	2918.98
Light	0.86	0.44	2.00	3636.37	1818.19
Glare	0.73	0.44	1.00	707.60	707.60
Age	0.42	0.53	1.00	5613.91	5613.91
age*light*Ped. Loc.	1.00	0.54	3.00	2938.58	979.53
age*Speed*light	0.11	0.80	1.00	1.83	1.83
age*light	0.22	0.80	2.00	952.73	476.36
Speed*Ped. Loc.	0.13	0.89	2.00	110.16	55.08
age*Speed	0.01	0.93	1.00	6.05	6.05

Analysis of the means with respect to forward lighting indicates that there might be a practical reduction in drivers' ability to detect pedestrians when on-demand lighting is utilized. In Figure 18, the mean detection distance is shown for the three forward lighting conditions, indicating a reduction in detection distance of 25% when 320 m forward on-demand lighting is used versus continuous overhead lighting. The 160 m forward light condition resulted in a 33% detection distance reduction compared to the continuous lighting condition. The difference in detection distance between the two on-demand lighting conditions appears not to be significant since the error bars overlap. Again, the analysis indicates that, for this study, the reduction in detection distance is not statistically significant at a 95% confidence level with respect to all of the forward lighting conditions.

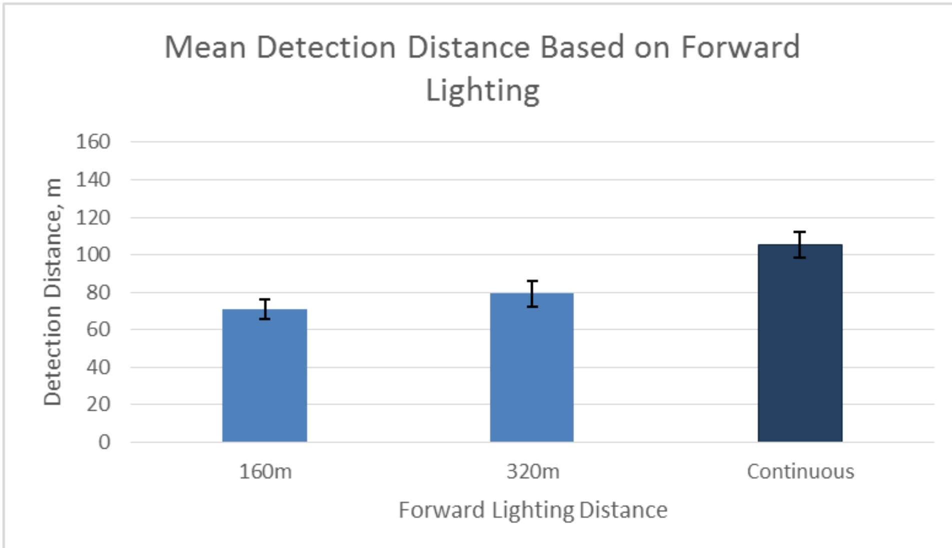

Figure 18. Variation in pedestrian detection distance based on forward lighting.

As expected, the older group detected pedestrians later than the younger group. However, the difference was not statistically significant for this study. The older group, whose mean age was 65.4 years, detected pedestrians at a mean distance of 74 m, while the younger group, whose mean age was 24.0 years, detected pedestrians at a mean distance of 97 m, (Figure 19). This difference is likely due to the older age group's lower visual acuity and UFOV scores (Table 13).

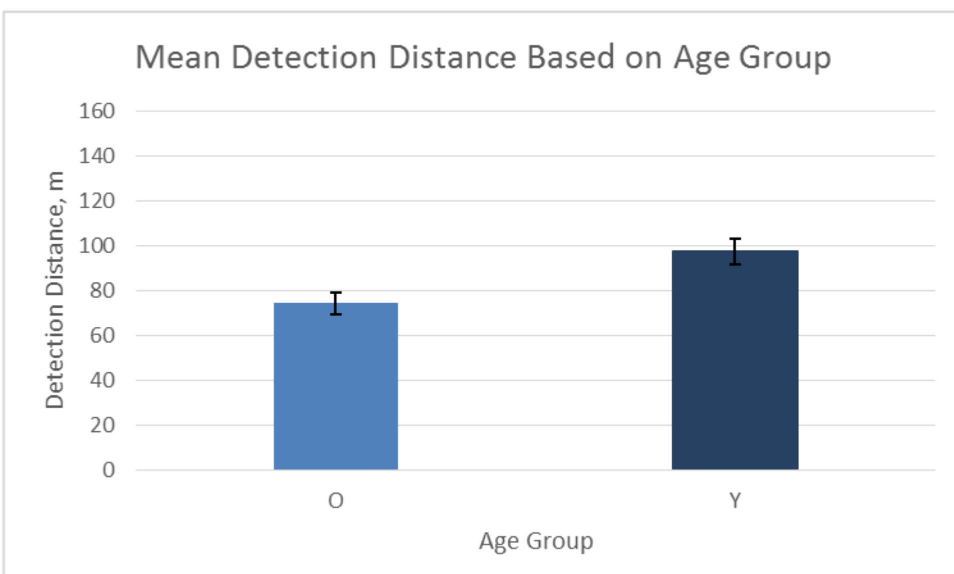

Figure 19. Pedestrian detection distance by age group.

The presence of an oncoming glare-producing vehicle had a practical effect, reducing detection distance by 17 m (Figure 20), as expected.

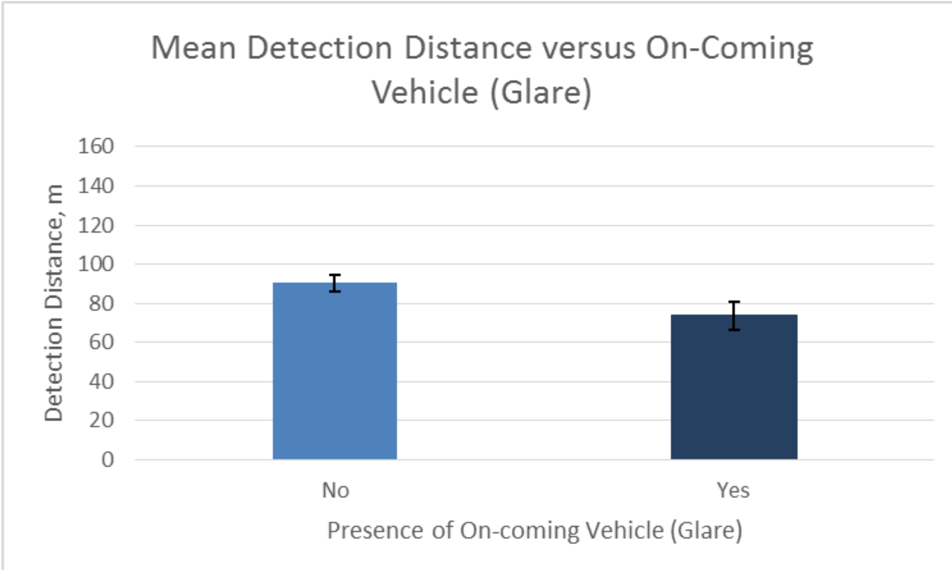

Figure 20. Detection distance in the presence of a glare-producing oncoming vehicle, also with on-demand lighting.

The difference in detection distance based on speed was very small (only about 2.5 m) and not statistically significant (Figure 21), as shown by the error bars for both speeds in the graph below.

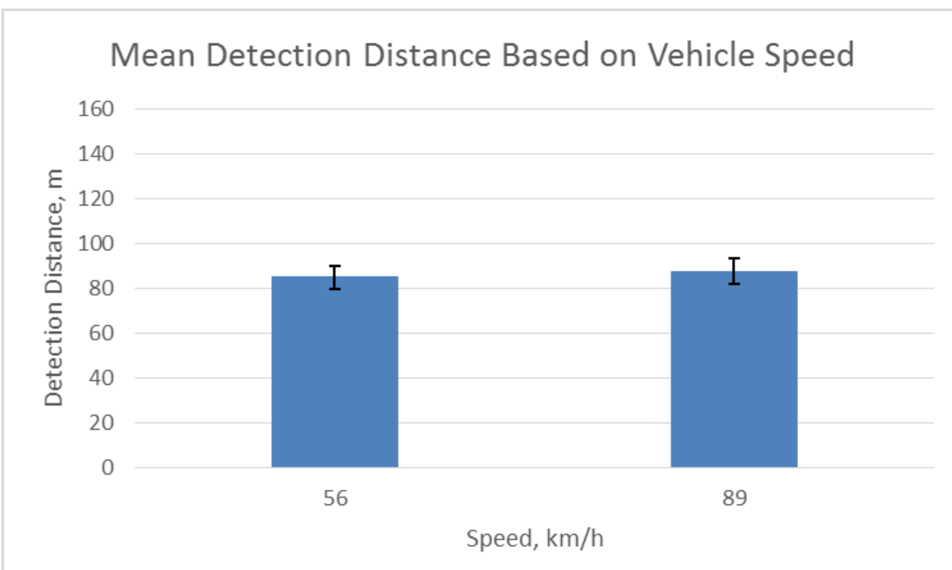

Figure 21. Detection distance based on vehicle speed.

While there is not a significant difference between detection distances at different speeds, there are practical differences between detection distances when speed and forward lighting interact. As Figure 22 and Figure 23 show, there appears to be a correlation between detection distance and forward lighting at higher speeds (89 km/h [55 mph]), where the detection distance appears to be proportional to the lighting used. However, at lower speeds, participants performed more poorly when 320 m of forward lighting was used than when 160 m of lighting was used. This may have occurred because higher speeds require more attention to vehicle control than lower speeds. Also, drivers tend to look farther in front of the vehicle when traveling at higher speeds. At both speeds, the detection distance was longer when continuous lighting was used. However, the statistical analysis shows that detection distance versus lighting and speed is not quite significant at a 95% confidence level.

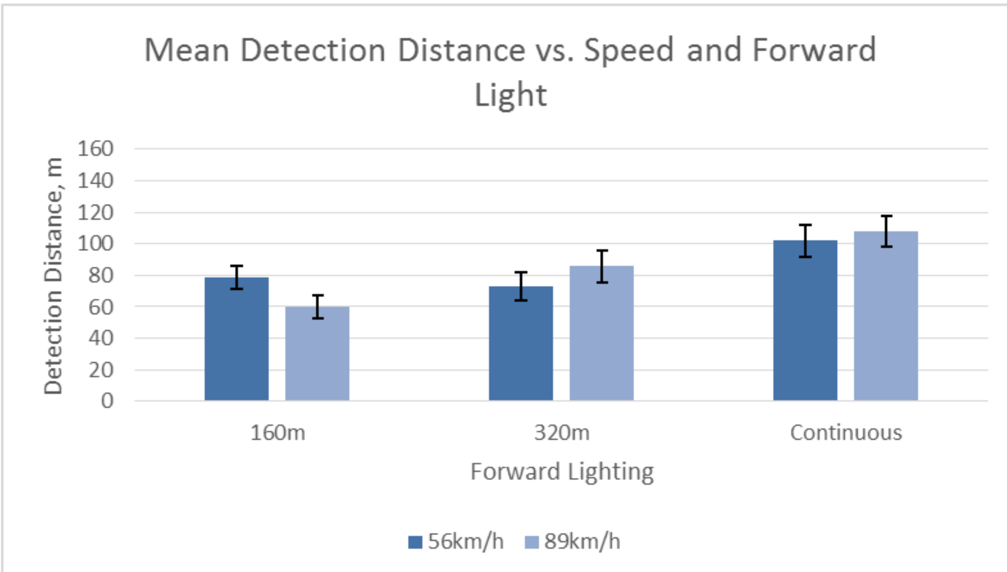

Figure 22. Detection distance versus forward lighting and speed.

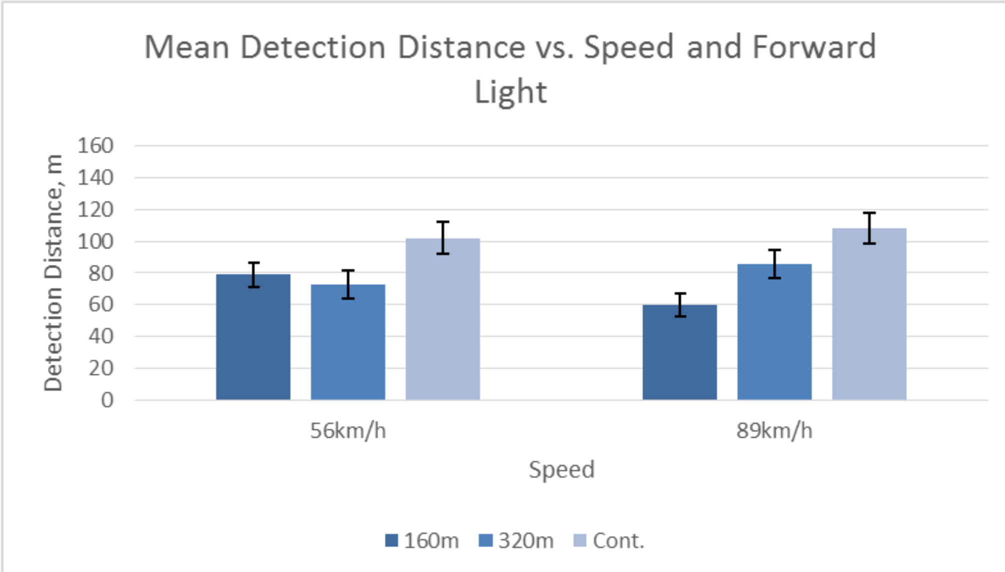

Figure 23. Detection distance versus speed and forward lighting distance.

As Figure 24 shows, the relationship between speed and lighting seem to be consistent for both age groups at higher speeds, but at lower speeds there appears to be a difference in the age groups.

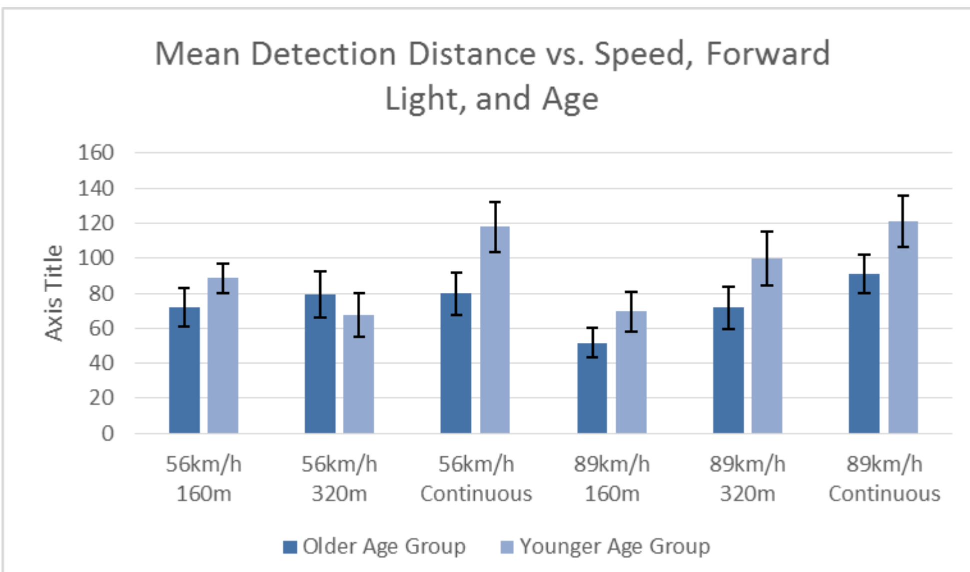

Figure 24. Detection distance versus speed, age and forward lighting.

Pedestrian Orientation Detection – Successful Detections

Of the 255 pedestrian presentations, participants were able to identify the direction the pedestrian was looking 203 times (80%). An ANOVA was performed on the missed versus unmissed pedestrian orientation detections with interesting results. As shown in Table 15, there were four statistically significant interactions related to participants missing the detection of the pedestrians' orientation: the interaction of speed and forward lighting, pedestrian location and forward lighting, and age with both of those interactions.

Table 15. ANOVA of Missed Pedestrian Orientations

Source	F Value	Pr > F	DF	Type III SS	Mean Square
Speed*light	1.05E+24	<.0001	2	0.001	0.000
age*Speed*light	1.04E+22	<.0001	1	0.000	0.000
light*Ped. Loc.	5825.4	0.0002	5	0.981	0.196
age*light*Ped. Loc.	2568.59	0.0004	3	0.260	0.087
Ped. Loc.	2.26	0.1	3	0.385	0.128
age*Ped. Loc.	1.4	0.2608	3	0.238	0.079
Speed*Ped. Loc.	2.59	0.4025	2	0.185	0.092
age*Speed	0.66	0.4314	1	0.050	0.050
glare	0.72	0.4449	1	0.109	0.109
age*Speed*Ped. Loc.	1.82	0.4642	2	0.130	0.065
Speed	0.41	0.5335	1	0.031	0.031
age*glare	0.18	0.6945	1	0.027	0.027
light	0.32	0.7304	2	0.059	0.030
age*light	0.31	0.7391	2	0.057	0.029
age	0.06	0.8084	1	0.062	0.062

The interaction between speed and forward lighting is shown in Figure 25. As the bar graphs show, the differences in the missed orientation detection for the two speeds in the experiment versus forward lighting conditions was within the error bars. Also, the correlation between forward lighting and percent missed for the 56 km/h (35 mph) condition is approximately linear, with misses decreasing as forward lighting increases. The correlation for the 89 km/h (55 mph) factor versus forward lighting is different as can be seen in Figure 25.

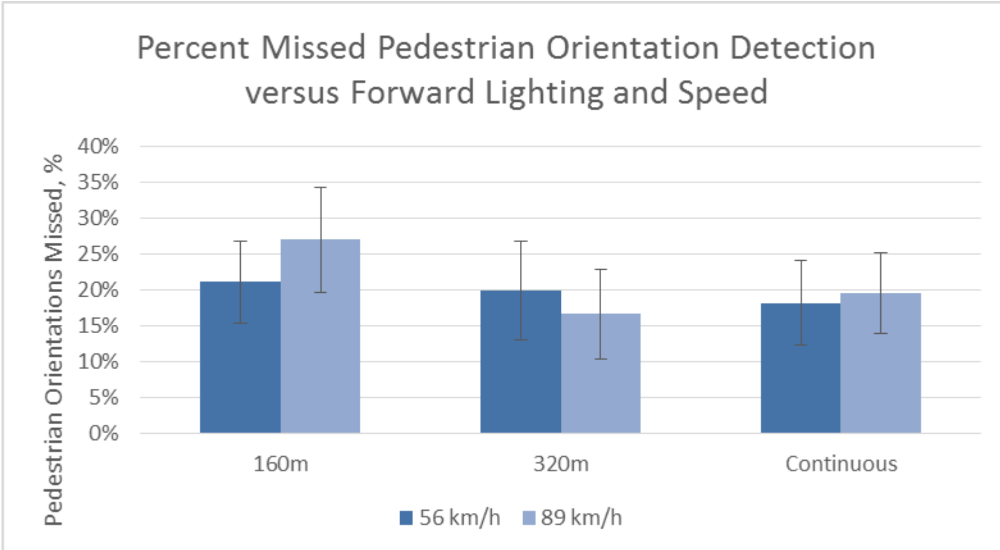

Figure 25. Missed pedestrian orientation detection percentage based on forward lighting and speed.

The interaction of forward lighting and pedestrian location was more complex (Figure 26).

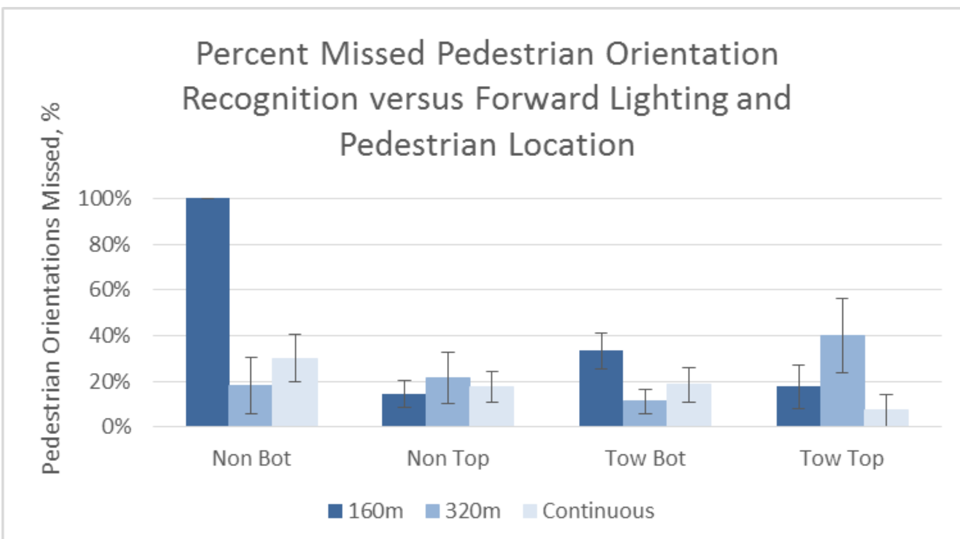

Figure 26. Missed pedestrian orientation detection percentage based on forward lighting and pedestrian location.

Pedestrian Orientation Detection Distance

For the remaining successful identifications of pedestrian orientation, an ANOVA was performed on the orientation detection distance versus the forward lighting condition and other factors (Table 16). As the results show, the only significant factors were the location of the pedestrians (Ped. Loc.), and speed. The interaction of age and speed was also nearly significant. Lighting was not a significant factor in the analysis. However, as Figure 27 shows, there appears to be a practical difference related to forward lighting that is similar to the detection distance relationship seen in Figure 18.

Table 16. Pedestrian Orientation ANOVA

Source	F Value	Pr > F	DF	Type III SS	Mean Square
Ped. Loc.	8.33	0.0009	3	20150.3	6716.75
Speed	12.29	0.008	1	3012.11	3012.11
age*Speed	3	0.1217	1	734.596	734.596
Age	1.32	0.2706	1	7640.44	7640.44
light*Ped. Loc.	5.18	0.3168	4	25038.8	6259.69
age*light	0.75	0.4896	2	3691.22	1845.61
age*Ped. Loc.	0.81	0.5054	3	1948.63	649.542
Glare	0.56	0.5897	1	281.212	281.212
age*glare	0.33	0.6669	1	165.631	165.631
Light	0.4	0.6754	2	1981.72	990.861
age*light*Ped. Loc.	0.02	0.9159	1	21.3363	21.3363

While the pedestrian orientation recognition distance versus speed and orientation recognition distance versus pedestrian location was significant from the analysis standpoint, the t or Tukey tests failed due to insufficient degrees of freedom. Therefore, it is not known if the differences were statistically significant. However, there seems to be a practical difference in the orientation detection difference based on forward lighting (Figure 27) that appears to be similar to the results shown in Figure 18.

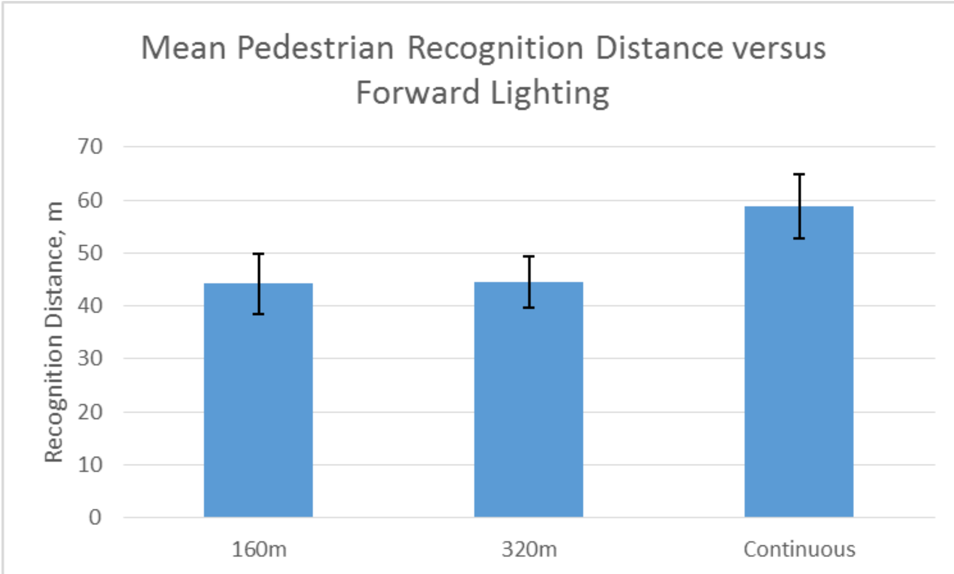

Figure 27. Pedestrian orientation detection distance versus forward lighting.

Figure 28 shows a practical difference in the orientation recognition distance based on the pedestrian location. The variation in this case, however, did not seem to be correlated to either vertical illuminance or lighting behind the vehicle.

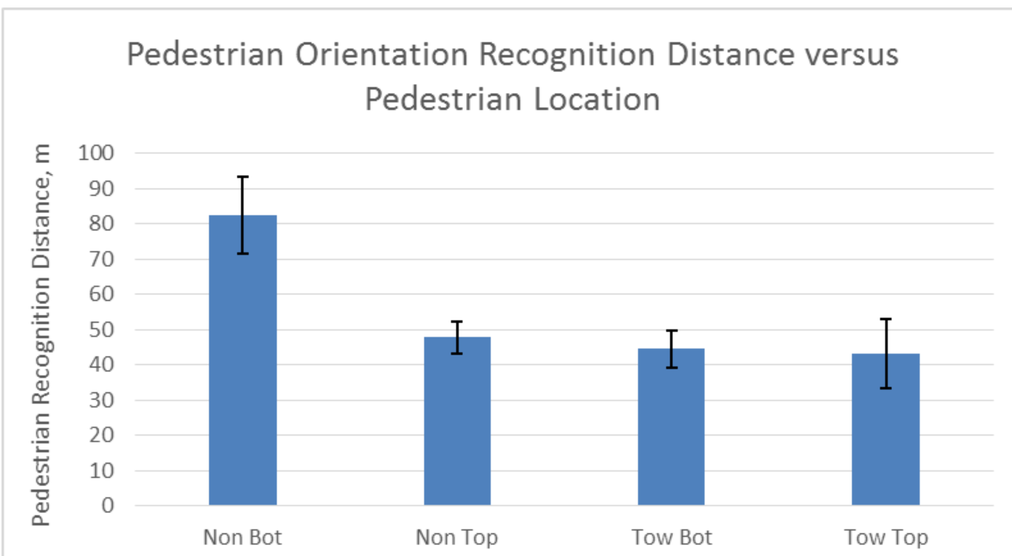

Figure 28. Mean pedestrian recognition distance versus pedestrian location.

While the analysis indicated speed was significant, both the means and t tests indicated the differences were not significant (Figure 29).

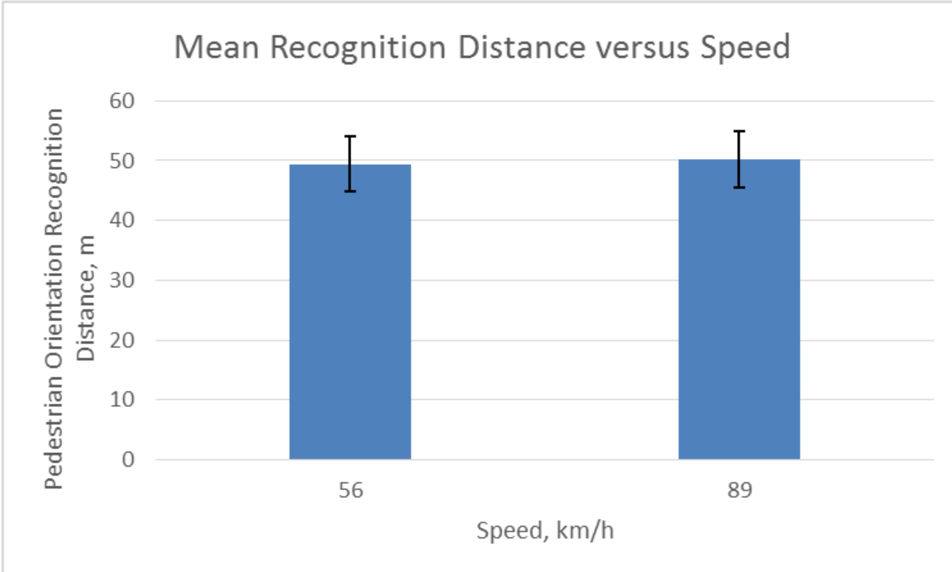

Figure 29. Mean pedestrian recognition distance versus speed.

Pedestrian orientation recognition distance versus speed and age interaction, while not statistically significant, seems to have a practical difference, as illustrated in Figure 30, which shows increased speed resulted in longer recognition distances for the younger group and decreased recognition distances for the older group.

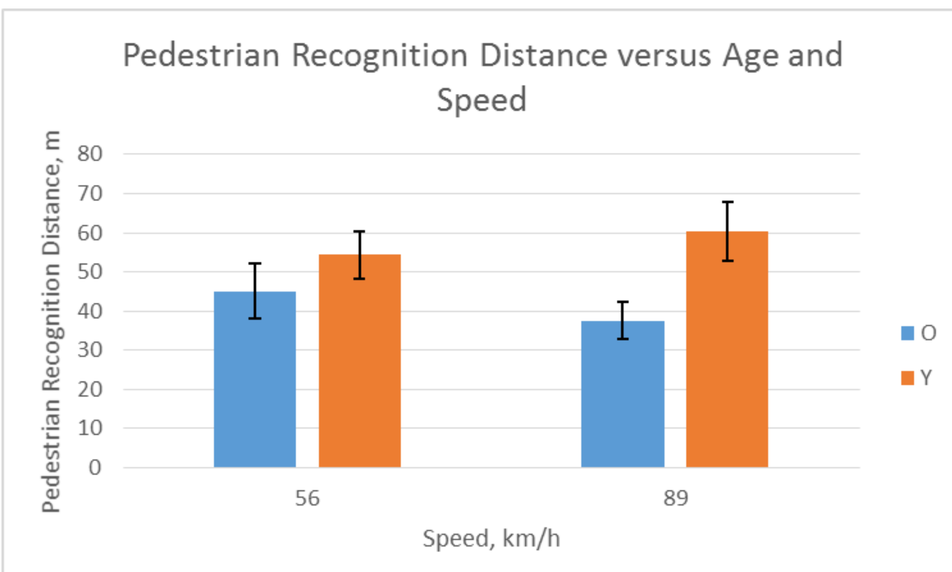

Figure 30. Mean pedestrian recognition distance versus speed and age interaction.

Target Detection

Out of the 105 target presentations during the experiment, 50 were missed completely. The targets missed were the smaller, 18 cm square gray targets, and were difficult to see even with continuous lighting. An ANOVA was performed with regard to misses as described in the data analysis section, and against the same, previously listed, independent variables used for the pedestrian detection. None of the factors or interactions that could be modeled were found to be significant at the 95th percentile. However, the means were still examined to determine if there were any practical differences.

As Figure 31 shows, the percentage of targets missed is nearly the same for each lighting condition.

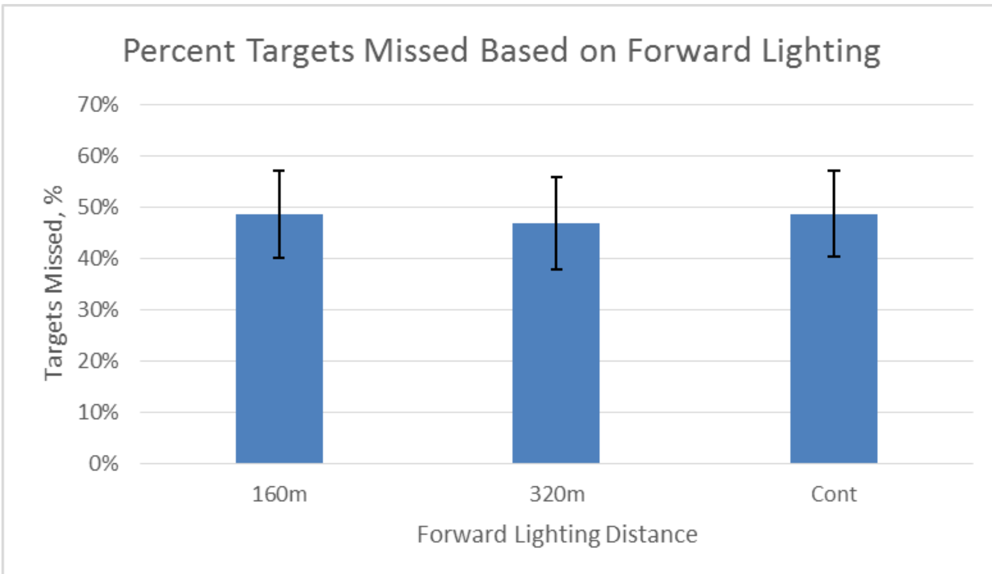

Figure 31. Percent targets missed based on forward lighting.

On the other hand, Figure 32 and Figure 33 show that more targets were missed at the higher speed (89 km/h [55 mph]) and that the older age group missed more targets. Since there were only 55 successful observations, the detection distance for the targets was not analyzed, as it is unlikely that any correlations would be statistically significant.

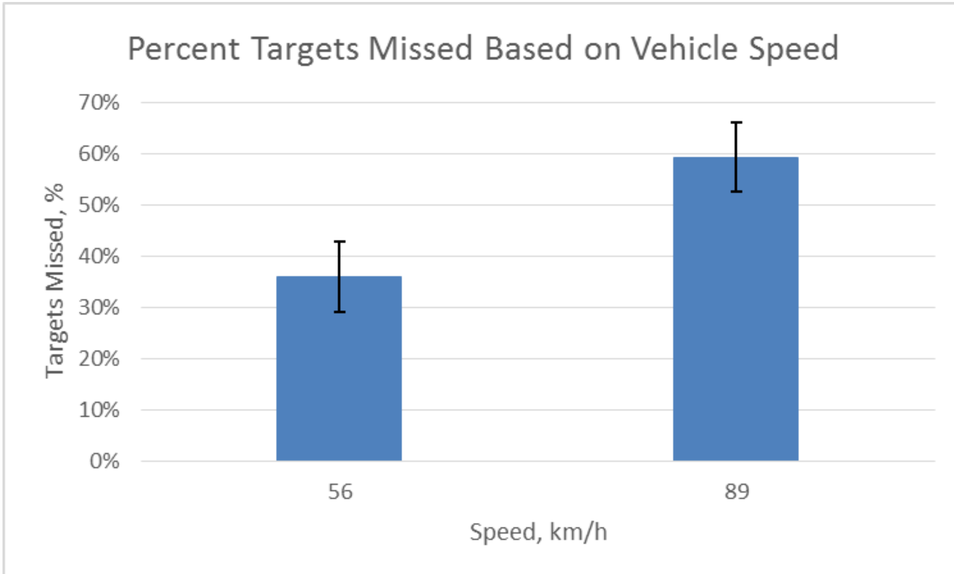

Figure 32. Percent targets missed based on vehicle speed.

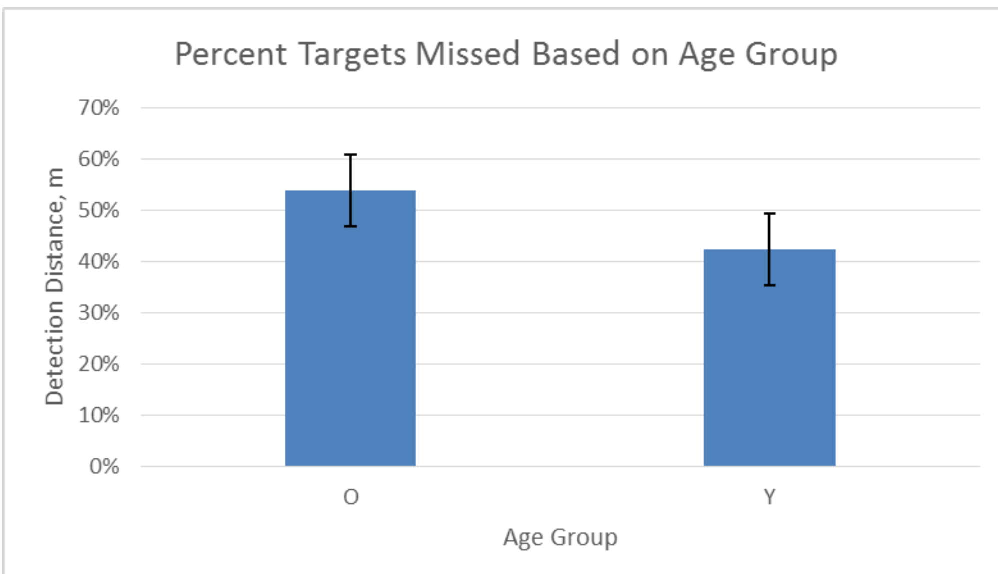

Figure 33. Percent targets missed by age group.

Survey Results

A survey was used to assess participants' reactions to and acceptance of the on-demand lighting system and its different lighting factors and interactions. After each run (i.e., half of a lap) on the Smart Road, participants were asked to answer six questions (Q1–Q6) on a Likert-type scale of 1 to 5. The questions are shown in Table 17 along with the mean responses and error for each question. Question 5 was only asked when there was an oncoming glare-producing vehicle present. All other questions were asked for every lap. As results show, participants rated the helpfulness of forward lighting favorably at 4.00 (Q1). They also felt that the overall lighting condition allowed them to drive safely at the speed they were directed to drive (Q6; rating of 4.08). Participants did not find the lighting in front of or behind them to be particularly distracting—the lighting behind them was rated near neutral at 2.6—nor did they find the oncoming vehicle condition to be distracting.

Table 17. Survey Questions, Mean Responses, and Similarity

Question	Mean	Error
1. How much did the lighting in front of you help you? (1-5; 1 = not helpful, 5 = extremely helpful)	4.00	+/- 0.06
2. How much did the lighting in front of you distract you? (1-5; 1 = not distracting, 5 = extremely distracting)	1.91	+/- 0.06
3. How much did the lighting behind you help you? (1-5; 1 = not helpful, 5 = extremely helpful)	2.62	+/- 0.07
4. How much did the lighting behind you distract you? (1-5; 1 = not distracting, 5 = extremely distracting)	1.94	+/- 0.07
5. Was the oncoming lighting and vehicle distracting? (1-5; 1 = not distracting, 5 = extremely distracting)	2.03	+/- 0.12
6. Did you feel this lighting condition allowed you to drive safely at this speed? (1-5; 1 = Very Unsafe, 5 = Very Safe)	4.08	+/- 0.05

The answers to each question were analyzed in a standard statistical software package against the lighting conditions, speed, age, etc. ANOVAs for each question were not possible due to non-normal distribution of answers. Instead, an analysis of the means was conducted; as shown in Figure 34, there is little difference in the question responses between age groups, except for Q1 and Q5. The younger age group found the oncoming lighting more distracting (rating of 2.3) than the older group. The difference may be due to older drivers' increased experience and greater ability to cope with glare conditions. It could also be due to the older group's lower visual acuity resulting in lower disability glare. The older group rated the helpfulness slightly higher than the younger group.

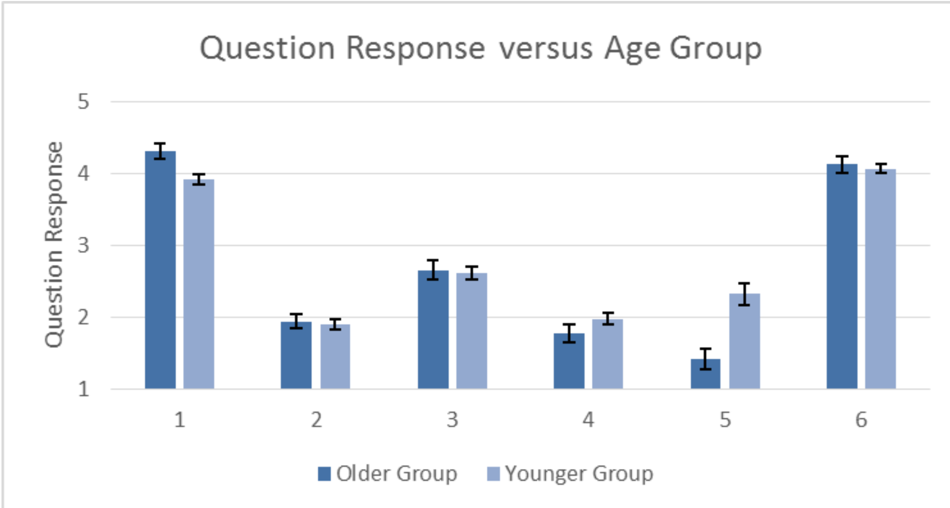

Figure 34. Mean question responses versus age.

Figure 35 shows the mean question responses to the forward lighting condition. The similar responses to Q1 and Q6 and the general increase in rating with increasing lighting forward of the vehicle indicates that participants' feelings toward the safety and helpfulness of the forward lighting condition are positively correlated to the amount of forward lighting available. However, for Q1, participants rated the 160 m forward lighting and the 320 m forward lighting condition an an average rating of 3.86 and 3.94, respectively. Each of these ratings were only slightly below the average rating for the continuous lighting of 4.19, all of which were very near to "helpful". The Q6 responses were very similar regarding the participants feeling of safety, with means of 3.94, 3.98, and 4.31 for the forward lighting conditions of 160 m, 320 m, and continuous, respectively.

The responses to Q2 show the distraction level of the forward lighting is inversely correlated to the amount of forward lighting available – less forward lighting was considered slightly more distracting. While the responses to Q3 and Q4, regarding the lighting behind the vehicle helpfulness/distraction level, appeared to be somewhat related to the forward lighting, the continuous rearward lighting condition always occurred with the continuous forward lighting condition, and there is little difference in the mean responses to Q3 and Q4 with respect to the 160 m forward lighting and 320 m forward lighting. Responses to Q5 indicate that oncoming on-demand lighting was only minimally distracting to drivers under the forward lighting condition, with means near 2 for all forward lighting conditions.

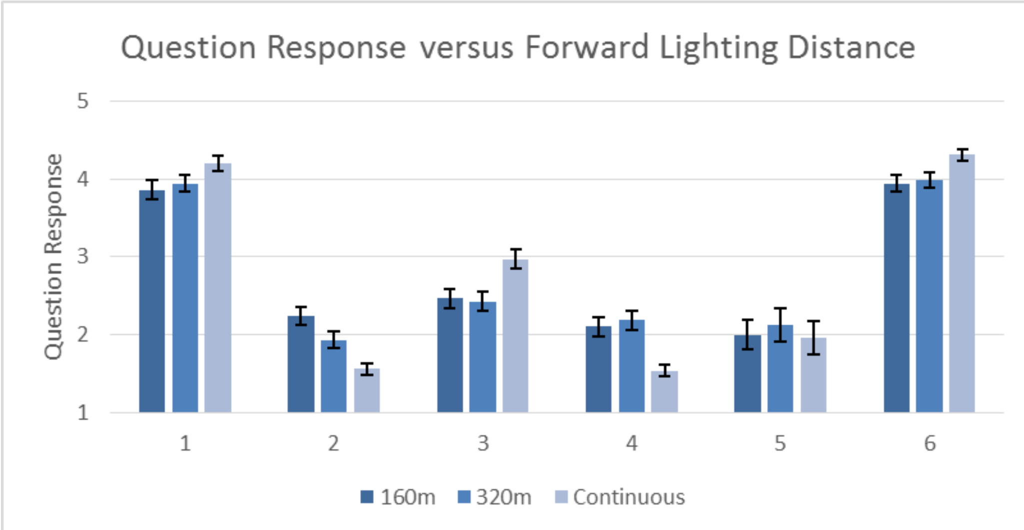

Figure 35. Mean question responses (by question) with respect to forward lighting.

Figure 36 shows the mean question responses under the rear lighting condition. For Q3, the helpfulness of the lighting behind the vehicle was rated lowest for 0 m at 2.1, slightly higher at 2.6 for 80 m and 160 m on-demand rearward lighting settings, and highest at 3.0 (nearly neutral) for the continuous lighting condition. With the exception of the 0 m lighting behind the vehicle, the responses to Q3 seem to agree that the lighting behind the vehicle does not provide help in the driving task, which requires focus by the driver on the area in front of the vehicle. Participants rated the average distraction of the lighting behind the vehicle (Q4) to be fairly low at 1.94, but found the 0 m lighting behind the vehicle condition to be more distracting, but still neutral, with a survey response of nearly 3.

The responses to Q1 and Q6 are similar for the lighting behind the vehicle condition. The 0 m lighting behind the vehicle conditions was rated the lowest in both cases and the continuous lighting condition rated the highest; however, the 80 m condition was rated higher than the 160 m condition, a non-linear relationship for both Q1 and Q6. Also of note is that the mean responses for Q1 were similar for the 80 m, 160 m, and continuous rearward lighting conditions at 4.09, 4.02, and 4.19, respectively. The differences are much smaller than the error bars in Figure 36. The responses to Q2 are inversely correlated to the amount of lighting available behind the vehicle: when there was less lighting behind the vehicle, the forward lighting was considered slightly more distracting. The average response for Q1, Q2, and Q6 to the 0 m rearward lighting condition seems to support the response to Q4 which indicates that the 0 m rearward lighting condition was distracting to the drivers. The average responses to Q5 did not seem to correlate with rearward lighting condition.

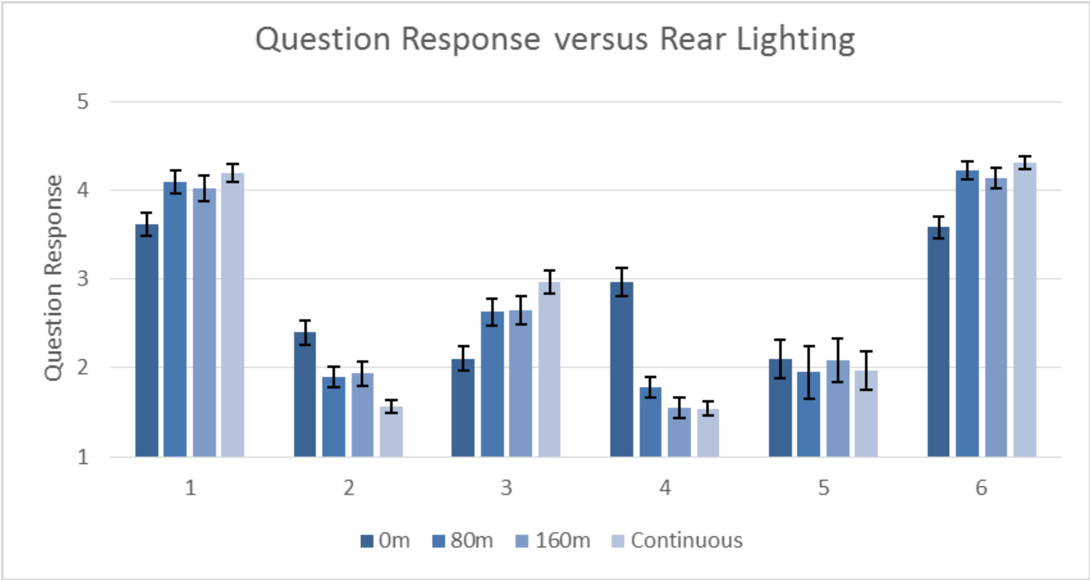

Figure 36. Mean question responses (per question) with respect to lighting behind the vehicle.

The responses, by question, to forward lighting and lighting behind the vehicle interaction questions (Figure 37) seem to be somewhat correlated to the total amount of light available, reflecting the observations for each lighting condition separately. The error bars for Q5, concerning glare, are larger because there were fewer observations, which makes it difficult to draw any conclusions about this interaction. However, it is obvious from participants' ratings that they found the lighting behind the vehicle level of 0 m to be much more distracting than all other conditions. Another interesting apparent trend is that the lighting conditions of 160 m forward and 80 m rearward were more favorable than the 160 m forward and 160 m rearward conditions. There may be a relationship between the amount of forward lighting used and lighting behind the vehicle needed for drivers to be comfortable. As exploring this relationship was outside the scope of the present study, it would be beneficial to do so in future work.

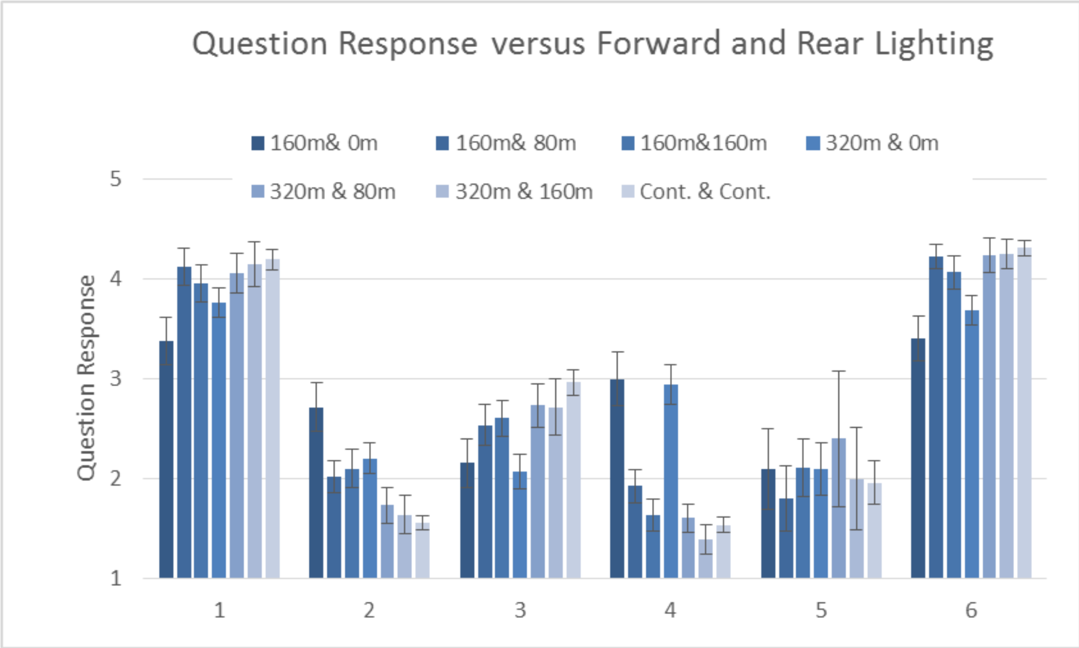

Figure 37. Mean question responses (by question) with respect to forward lighting and lighting behind the vehicle interaction. (The first number in each legend entry is the forward lighting condition and the second number is the lighting behind the vehicle condition.)

Speed Control

For the last two runs of the experiment, no targets or pedestrians were presented. The participants were instructed to drive whatever speed was comfortable, up to 89 km/h (55 mph). For these two laps, the on-demand lighting system was set to 160 m forward and 80 m lighting behind the vehicle for one lap, and 320 m and 160 m for the other lap. Since one run was uphill and one downhill, some participants were presented the 320 m lighting on the uphill run, while others were presented the 160 m condition on the uphill run. ANOVA showed that the speed was likely dependent on the forward lighting available with a $Pr > F = 0.044$ and an F value of 4.89. The mean speed versus forward lighting is shown in Figure 38. As the figure shows, the difference is small, only 2.5 km/h (about 1.5 mph), so it is not much of a practical difference and only slightly bigger than the error. Speed was not significantly different between age groups (Figure 39).

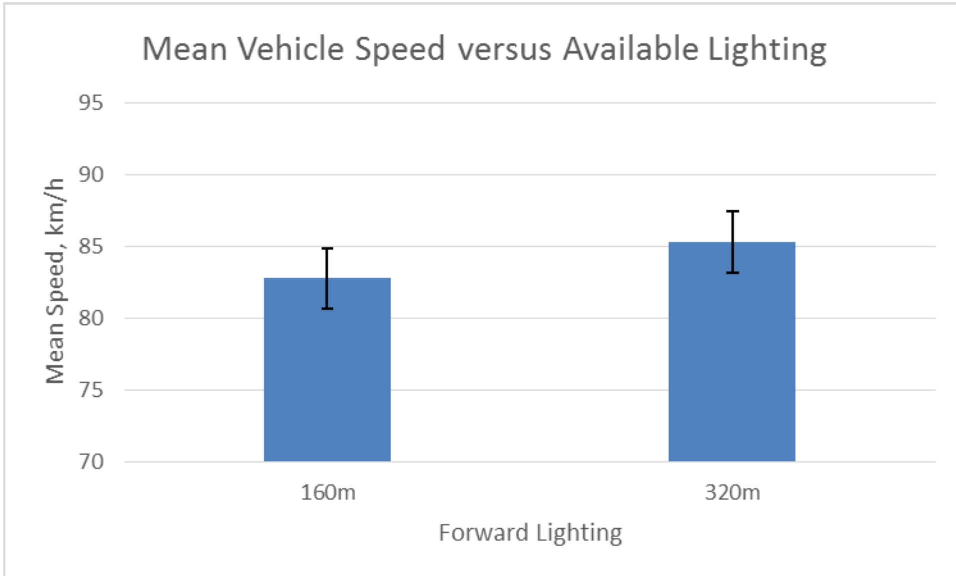

Figure 38. Mean speed versus forward lighting.

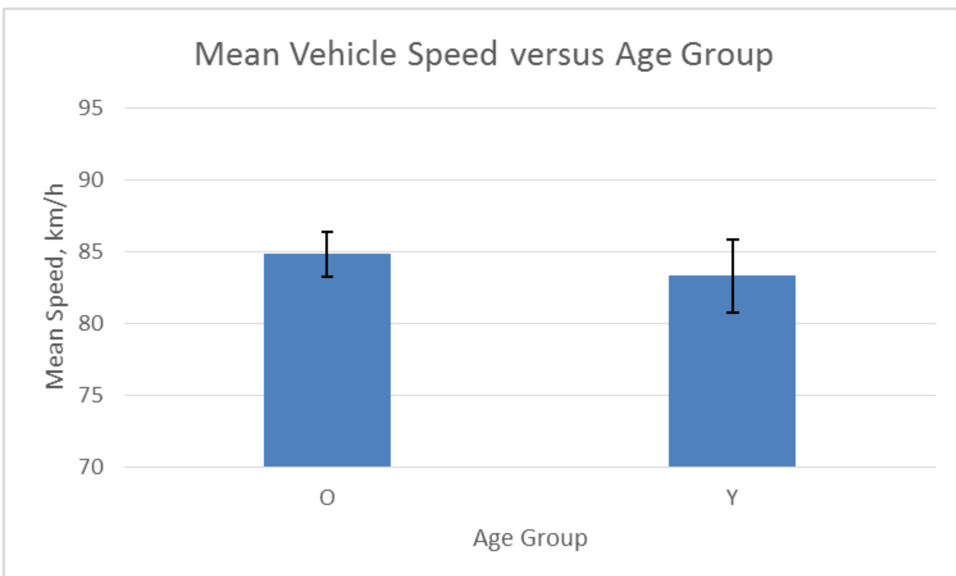

Figure 39. Mean speed versus age group.

Speed versus the interaction of forward lighting and age group showed that the older age group drove slightly faster (2 km/h) for the 320 m lighting condition but there was virtually no difference in mean speeds for the two age groups for the 160 m forward lighting condition (Figure 40).

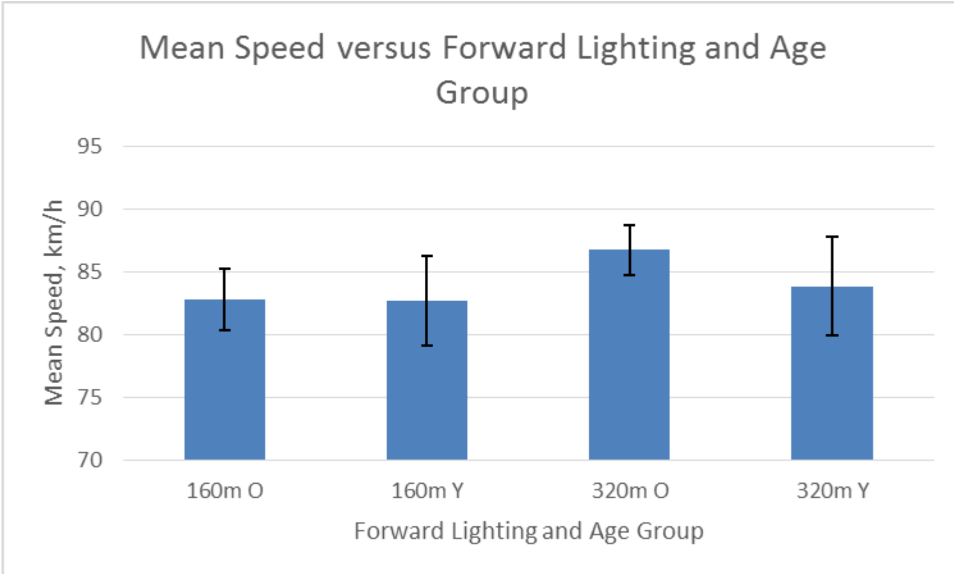

Figure 40. Mean speed versus the interaction of forward lighting and age group.

Discussion

The on-demand lighting system performed nearly flawlessly for the duration of the project, aside from one night when there may have been issues with the GPS signal not reaching the server. As the appropriate data was not available to further investigate this issue, it could not be confirmed why the signal was disrupted, however it may have been due to electromagnetic interference from a very large solar flare (X1.8 event) that occurred earlier in the day (December 19, 2014). This flare could have disrupted the DSRC or GPS signals, preventing the software from locating the test vehicles. Since X-class flares (the largest classification of solar flares) are not uncommon and can disrupt GPS signals, this could have an impact on any CVI system that relies on the GPS-derived position of the vehicle. A backup approach to mitigate this issue may be to disable the on-demand control system when X-class solar flares are expected.

Results of this study appear to show that participants generally accept the use of on-demand lighting. A minimum of 1 pole (or 80 m) of lighting seems to be required behind the vehicle to keep the lighting behind the vehicle from being distracting.

The analyses showed no statistical significance between the amount of forward lighting available and the detection of on-road pedestrians or recognition of pedestrian orientation. However, there does appear to be some practical reduction in both detection distance and orientation recognition distance for on-demand lighting versus continuous lighting. There appears to be a complex interaction between the amount of forward lighting and detection distance when on-demand lighting is utilized at different speeds for the two different age groups as shown in Figure 41. This relationship could be caused by several factors that were not included in this study: eye glance behavior, confidence in driving highway speeds in the dark in an unfamiliar situation, etc., that should be further investigated with a more specific study.

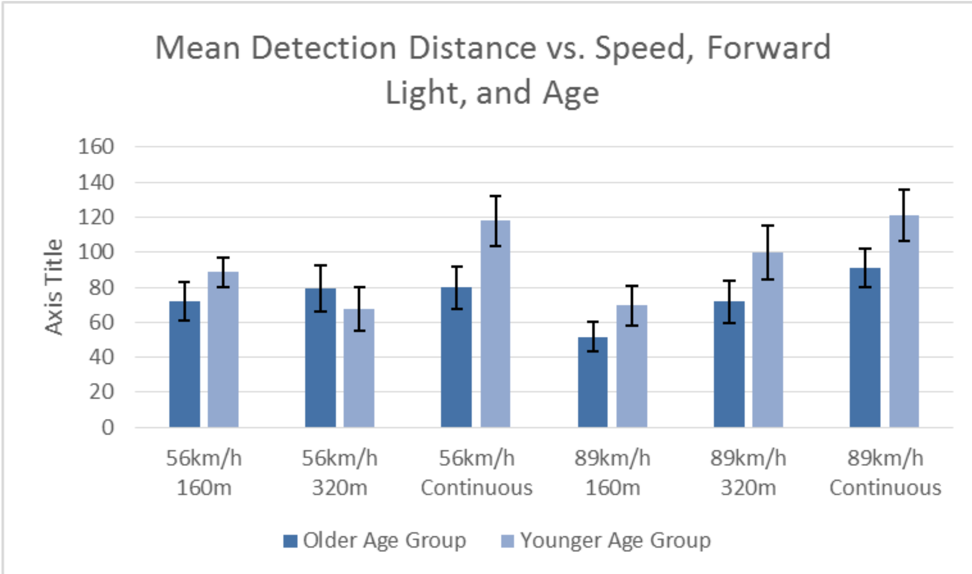

Figure 41. Detection distance versus speed, age and forward lighting.

Detection distance varied significantly depending on the location of the pedestrian presentation and the vertical illuminance. Plotting the average vertical illuminance versus mean detection distance for each pedestrian presentation location shows the detection distance generally increases as vertical illuminance of the pedestrian increases (Figure 42). However, the condition of "Tower-side – high vertical illuminance" has a lower detection distance than expected based on vertical illuminance alone.

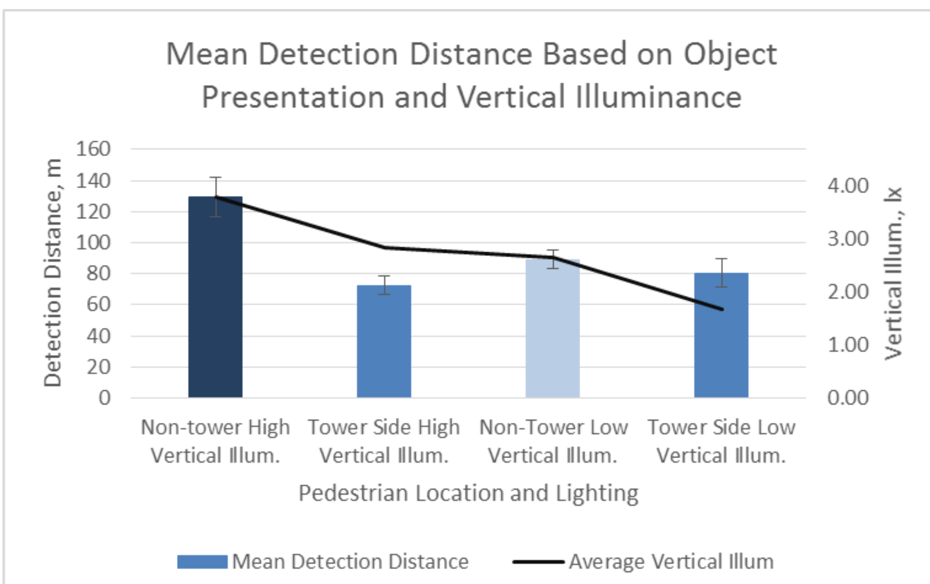

Figure 42. Detection distance versus location and vertical illuminance.

The discrepancy between visual performance and vertical illuminance may be due to the visual clutter that exists on the tower side of the Smart Road. This can be seen in Figure 43. The different locations had different backgrounds, ranging from dark sky to partially-lit embankments and weather poles, which could also dramatically affect contrast.

Figure 43. Scene clutter on the tower side of the Smart Road.

Another possible explanation might be the on-demand lighting. Forward lighting did not seem to correlate with the location detection differences. Due to the limitations of the study, lighting behind the vehicle was not a balanced treatment. As such, lighting behind the vehicle had to be studied as a covariate. To see if lighting behind the vehicle was affecting the detection distance for the different pedestrian locations, the mean detection differences based on pedestrian location were plotted against the average lighting behind the vehicle for each of the pedestrian presentations. Since the full length of the lighted section of road was 1,120 m, this value was assigned to the continuous lighting behind the vehicle condition as an approximation.

As Figure 44 shows, there appears to be a correlation of detection distance with the lighting behind the vehicle. As discussed in the analysis section, the partial factorial presentation required that the covariance of the lighting behind the vehicle be analyzed versus the various dependent variables, in this case pedestrian detection distance. Generally, the luminance of the background of a scene is due to horizontal illuminance of the nearest luminaire. However, the vertical illuminance of the pedestrian or target is the sum of the contribution of the vertical illuminances of all of the luminaires. Therefore, it is likely that vertical illuminance of the pedestrians or targets was lower under the on-demand conditions, and that it was correlated with the total number of luminaires, including those behind the moving vehicle, that were on before the pedestrian. This may explain the apparent correlation with lighting behind the vehicle.

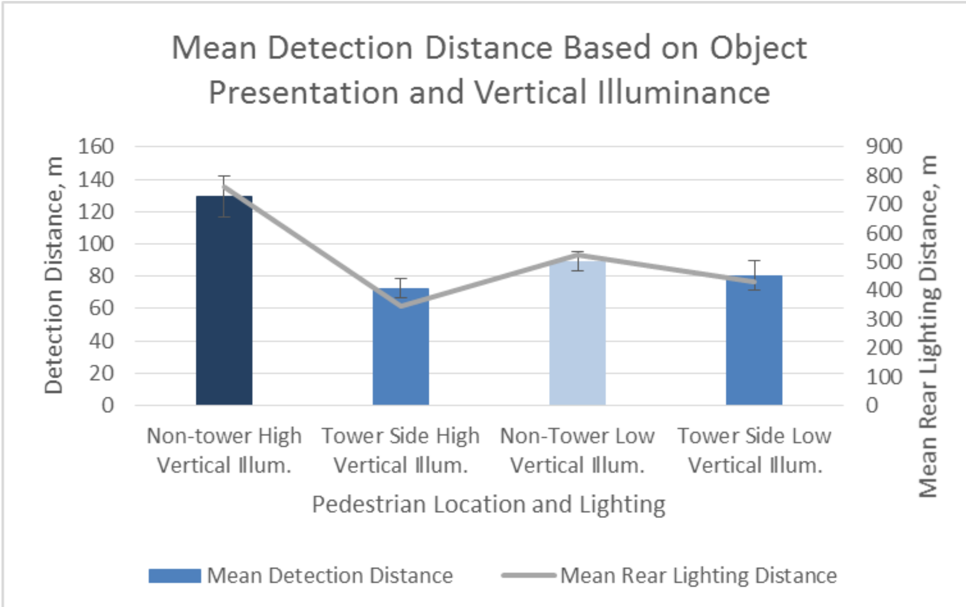

Figure 44. Detection distance versus object location and mean lighting behind the vehicle distance.

Rearward light also appears to have had an inverse effect on the number of missed pedestrian orientations versus forward lighting and pedestrian location, with more misses occurring under conditions with less rearward light (Figure 45 and Figure 46).

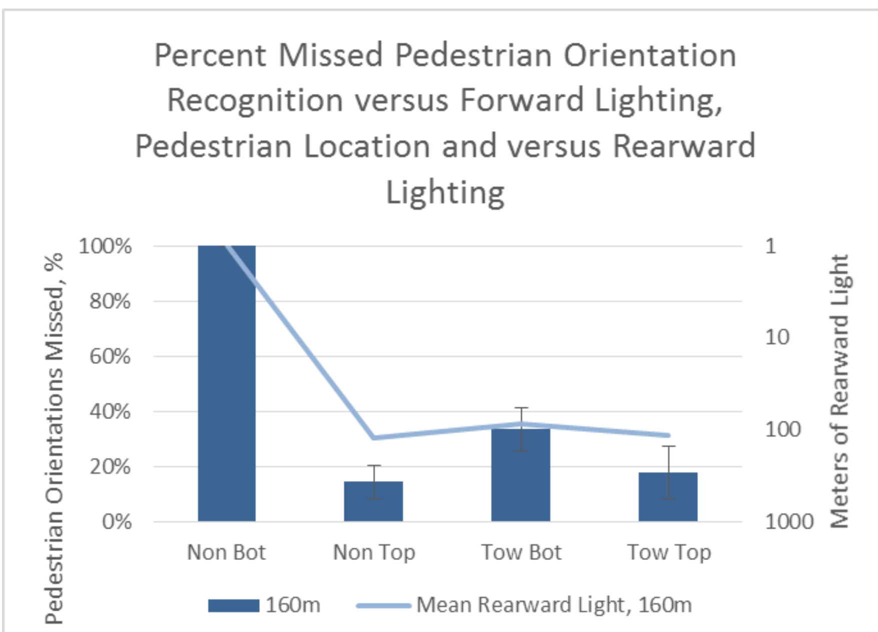

Figure 45. Missed pedestrian orientation detection percentage versus pedestrian location and lighting behind the vehicle for 160 m forward lighting.

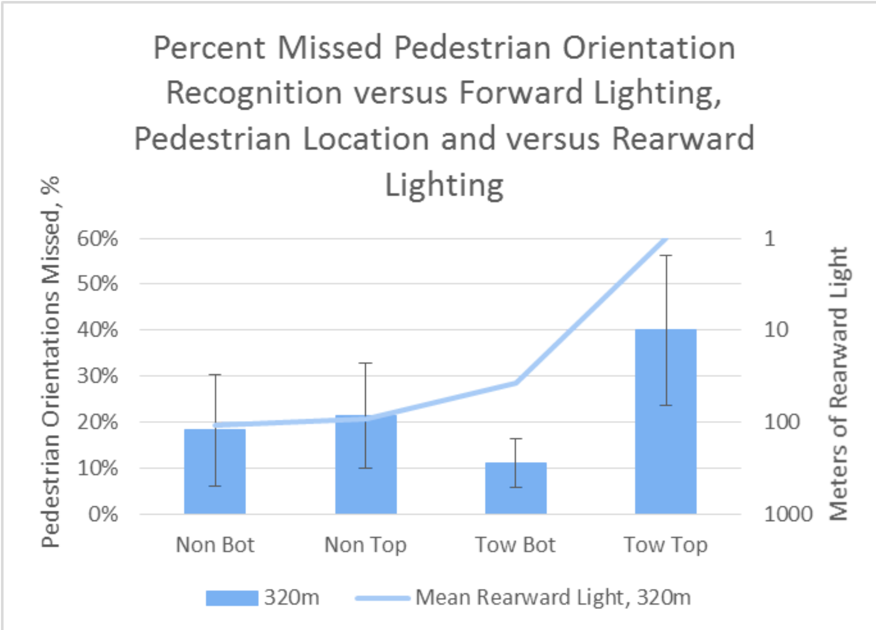

Figure 46. Missed pedestrian orientation detection percentage versus pedestrian location and lighting behind the vehicle for 320 m forward lighting.

On-demand lighting seems to have no statistically significant effect on the ability to detect targets on the side of the road. There also seems to be no interaction between on-demand lighting and glare from oncoming vehicles that affects drivers' ability to detect on-road hazards.

In this study, the forward lighting and lighting behind the vehicle conditions were based on multiples of luminaires at 80 m spacing (i.e., 320 m = 4 luminaires). While the results are all presented in meters of lighting, the study did not change the luminaire spacing of 80 m. So it is not clear whether the relationships involving forward lighting or lighting behind the vehicle are based on the number of luminaires utilized or the distance of lighting. It may be worth clarifying the difference with a future study that varies the luminaire spacing along with the distances of the forward lighting and the lighting behind the vehicle.

Finally, reducing the amount of on-demand lighting in front of the vehicle did seem to lower drivers' comfortable driving speed. However, the difference was insignificant at 2.5 km/h (1.5 mph), even when the lighting was reduced by half. When 320 m lighting was utilized, the mean speed was 82.5 km/h (approximately 50 mph). At this speed, the stopping distance is 205 feet (about 62 m), so participants had lighting that was six times the required stopping distance. At the 160 m lighting condition, there was still nearly three times more stopping distance of lighted roadway available than required. It is possible that the experiment didn't shorten the lighting distance enough to determine the relationship between speed and required lighting or lighting and speed control. Further study is warranted with forward lighting shortened to less than the stopping distance at 50 mph (82.5 km/h), since both forward lighting treatments were much longer than the needed stopping distances.

Conclusions and Recommendations

Conclusions

VTTI successfully developed and implemented a CVI-based, on-demand, just-in-time roadway lighting system and explored the human factors related to the system. The on-demand roadway lighting system studied in this project used DSRC, RSEs installed along the Virginia Smart Road, and central control of the luminaires.

The study found no statistically significant limitations to the on-demand lighting system with regards to participants being able to detect on-road hazards or pedestrians, the safety/visibility surrogate. The system was found to be largely acceptable by the 16 participants, with no difference between age groups. There appear to be some practical aspects that should be investigated related to visual performance and the amount of on-demand lighting (rearward and forward).

The on-demand lighting system was able to control the participants' speed. However, further study with shorter lighting distances is warranted to determine whether this effect is significant and to determine if there is a stronger relationship between speed and shorter lighting distances.

This study tested on-demand lighting versus some of the more challenging visual tasks facing vehicle drivers, with a positive outcome. As CVI technology becomes more available on vehicles and more prevalent in infrastructure, on-demand lighting will become a viable approach to improving safety at a lower cost than traditional or even dimming-adaptive lighting.

Future Research

The luminaire-control software allows researchers to control all of the luminaires on the Smart Road, including those not currently using LED technology. So, in the future, the Smart Road could be used in on-demand lighting experiments utilizing 40, 60 or 120 m luminaires spacing. This would enable further determination of whether the effects seen were related to distance or number of luminaires. The relationship between on-demand lighting behind the vehicle and detection distances should be further studied to better understand human vision in the highly complex visual environment of nighttime roadways.

Also, dimming on-demand lighting, as opposed to the Boolean approach used here, could result in different effects. Finally, shorter distances of on-demand lighting should be investigated to better determine the relationship between visibility and on-demand lighting as well as the limits of speed control utilizing on-demand lighting.

Finally, disruption of GPS or DSRC signals caused by X-class flares should be studied regarding CVI technologies. Given that the most useful information provided by CVI is the position of the vehicle, disruption of the wireless communication is a real risk that needs to be quantified and mitigated. The magnitude of the disruption is likely receiver-dependent so in order to mitigate the effects, either the specific GPS receiver would need to be tested, or a model of the effects would need to be developed to simulate the effect on specific hardware.

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