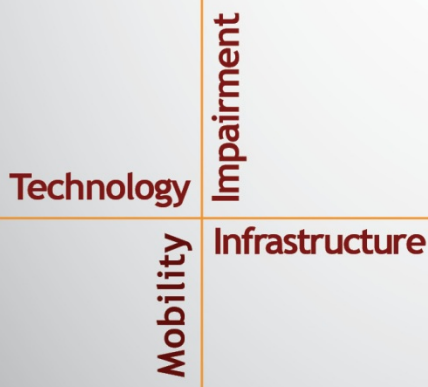# NSTSCE

**National Surface Transportation
Safety Center for Excellence**

4U Lighting – Cooperative Headlighting

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Impairment

Technology

Mobility

Infrastructure

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ACKNOWLEDGMENTS

ABSTRACT

The purpose of this project was to evaluate the effectiveness of an alternative cooperative headlighting method, dubbed 4U Lighting. A human-subjects study was conducted in which 12 participants 65 or older observed pedestrians under different lighting configurations and identified the moment when they were sure they could see a pedestrian. The participants drove a vehicle towards a static vehicle in the opposite lane around which the pedestrians were located. The distance at which participants could detect the pedestrian, termed the detection distance, was compared across lighting conditions and served as the measure of improvement in driver visual performance (visibility). Commercial connected vehicle hardware and protocols were used to communicate position between the two vehicles and to trigger the operation of the custom lighting control system. The system operated as expected and the data showed benefits to driver visual performance.

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LIST OF ABBREVIATIONS AND SYMBOLS

BSM	Basic Safety Message
CIE	International Commission on Illumination
DAS	data acquisition system
DF	degrees of freedom
DGPS	differential Global Positioning System
DSRC	Dedicated Short Range Communication
E_{gl}	glare source illuminance
F-value	variance of the group means
FHWA	Federal Highway Administration
GPS	Global Positioning System
HID	high-intensity discharge
k	age factor
L_b	background luminance
LED	light-emitting diode
L_o	object luminance
L_{seq}	equivalent veiling luminance
NHTSA	National Highway Traffic Safety Administration
Pr > F	the significance probability value associated with the F-value
SAE	Society of Automotive Engineers
SNK	Student-Newman-Keuls
V2V	vehicle-to-vehicle
VTTI	Virginia Tech Transportation Institute
Θ	eccentricity angle of the glare source

CHAPTER 1. INTRODUCTION

BACKGROUND

Nighttime driving is approximately three times more risky than daytime driving (Varghese & Shankar, 2007). As described in a 2007 report to Congress, two factors that contribute to the greater risk of nighttime driving are glare and veiling luminance (National Highway Traffic Safety Administration, 2007). This is particularly true when two vehicles traveling in opposite directions pass each other. As two vehicles approach one another at night, the visual performance of both drivers drops off dramatically, even when the drivers select low beams, because of disability glare. The headlight output of the oncoming car causes the driver's eyes to adapt to that light level, and scatter within the eyes reduces the contrast of the scene, which makes hazards and/or pedestrians on the side of the road practically invisible for a few seconds.

One solution to the problem of disability glare is to adapt the illumination from the headlights to the scenario. In cooperative headlighting, both approaching cars would reduce the output of their own headlights while projecting a white light from the driver's side of the car to light the roadway and shoulder for the oncoming driver (Figure 1). This would not require beam shaping, which is currently not legal under National Highway Traffic Safety Administration (NHTSA) rules (National Highway Traffic Safety Administration, 2004), but would likely involve dimming the lamp or completely turning off the driver's headlamp. However, the design of the optics would require some baffling, careful design, or rearward sensing to prevent a white light from being seen behind the vehicle, which is also not legal.
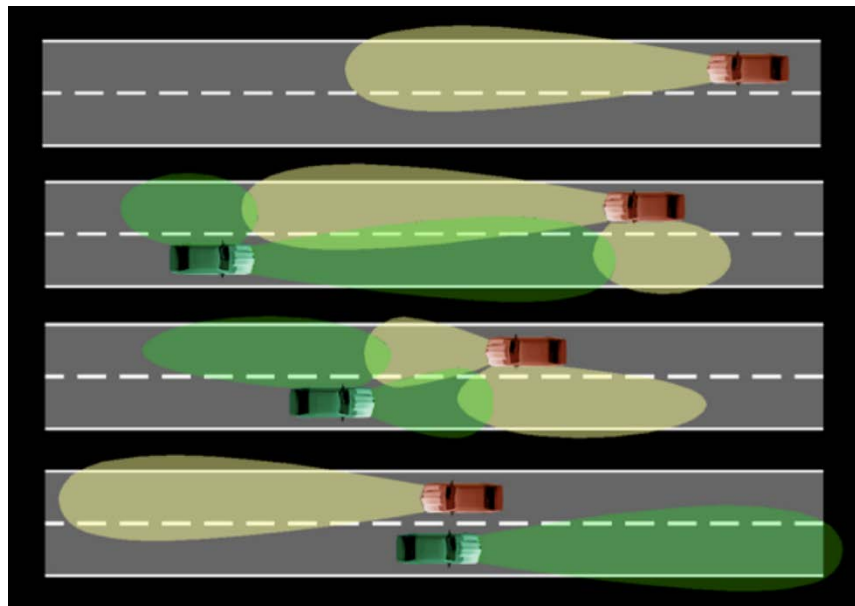

Figure 1. Illustration. Cooperative headlighting concept.

Cooperative headlighting will enhance visibility on undivided roadways at night and will improve the conspicuity of both road workers and vulnerable users such as pedestrians and bicyclists. By reducing the amount of light and dark adaptation that drivers will need to endure,

this system will also reduce eye fatigue, especially on busy two-lane roadways. The reduction in eye fatigue, in turn, will also reduce overall driver fatigue.

PROJECT APPROACH

The purpose of this project was to evaluate the effectiveness of an alternative cooperative headlighting method, dubbed "4U Lighting." A human subjects study was conducted in which participants observed pedestrians under different lighting configurations and identified when they could definitively see a pedestrian. The distance at which participants could detect the pedestrian, termed the "detection distance," was compared across lighting conditions.

LITERATURE REVIEW

Although nighttime traffic accounts for only 25% of total traffic, 49% of all fatalities occur at night, meaning that nighttime driving is approximately three times more risky than daytime driving (Varghese & Shankar, 2007). A lower rate of seat belt use, higher blood alcohol concentrations, and excessive speed have been found to be factors in the high nighttime fatality rate (Varghese & Shankar, 2007). However, Rea, Bullough, Fay, Brons, Van Derlofske, and Donnell (2009) found that when roadside illumination was installed, the accident rate decreased by 20% to 30% when similar road sections with and without roadside illumination were compared. Another study compared a section of road before and after illumination was installed and found that accidents decreased by 56% (Nishimori, 1973). This suggests that vehicular headlights as implemented today do not provide the same level of safety as roadside illumination.

Two types of glare impact a vehicle operator when meeting an oncoming vehicle: discomfort glare and disability glare. Disability glare is glare that prevents a person from seeing an object in the driving environment due to scattering in the ocular media and is a reduction in visual contrast. Disability glare can be directly measured by measuring the contrast of an object/pedestrian, which is also a direct measure of the visibility. Discomfort glare is glare that is hard or even painful to look at, but it is more subjective than objective. Discomfort glare is wavelength dependent, with blue sources causing more discomfort than other colors (Flannagan, Sivak, Ensing, & Simmons, 1989). Discomfort glare can be measured using a rating scale.

It is not feasible to install roadside illumination on all roads, and therefore drivers need to depend on headlights for nighttime visibility. One of the factors that limits the effectiveness of headlights on non-divided roads is the disability glare caused by vehicles in the opposing lane (Van Derlofske, Bullough, Dee, Chen, & Akashi, 2004). Common countermeasures to reduce the effect of glare that can be implemented in the United States include wide medians, glare screens in the median, polarized lighting, overhead lighting, and headlamp height (Mace, Garvey, Porter, Schwab, & Adrian, 2001). Aside from physical changes to the infrastructure or requiring actions by the driver such as using a hand to shield the eyes from the glare source, beam pattern advancement has been pursued, but it has not completely eliminated the problems.

Higher intensity headlights with precise beam patterns to diminish glare were introduced nearly two decades previously, but many complaints relating to discomfort glare have been submitted (National Highway Traffic Safety Administration, 2001). While research has continued, there

have not been significant changes in headlight standards in the United States. Some factors that hinder the effectiveness of these technologies include misaimed beams (about 50%) and dust or water on the surface of the lens scattering light and causing glare (Alferdinck & Padmos, 1988). In Europe, dirty lenses are considered an issue, and a lens cleaning function is required for brighter headlights (Regulation No. 48 of the Economic Commission for Europe of the United Nations).

Another major factor is the simple geometry of the headlamps of two cars passing each other and the drivers' gazes. When passing an oncoming car, we are faced with a dilemma: the car needs to illuminate the road ahead but, at the same time, should not illuminate the oncoming driver's eyes. The angle between the center of the road, where the headlight beam is strongest and the oncoming driver's eyes is very small (1 to 2 degrees at 50 to 100 meters of separation), and the smaller the angle between the light source and visual gaze, the more severe glare becomes (Vos, 2003).

Disability glare can be calculated based on the effect on the contrast of objects in the driving scene. Contrast is a measure of the difference between the luminance of an object and the background. The overall luminance of the scene can affect the contrast, as the human eye is nonlinear in response to varying luminance. There are many formulations that can be used for calculating contrast without glare, but the simplest is Weber contrast (Equation 1), where L_o is the luminance of the object and L_b is the luminance of the background.

$$C = \frac{L_o - L_b}{L_b}$$
<div align="right">**Equation 1**</div>

Disability glare is dependent on the equivalent veiling luminance, L_{seq}, which is dependent on the illuminance of the glare source, E_{gl}, the eccentricity angle Θ that separates the glare source and the line of sight, and k, which is age dependent. For Θ greater than 2 degrees, the formula for L_{seq} is (Adrian & Bhanji, 1991):

$$L_{seq} = \frac{kE_{gl}}{\theta^2}$$
<div align="right">**Equation 2**</div>

The formula for k is typically listed as:

$$k = 9.05\left(1 + \left(\frac{Age\ (in\ years)}{66.4}\right)^4\right)$$
<div align="right">**Equation 3**</div>

The contrast of an object in the presence of glare is then:

$$C = \frac{L_o - L_b}{L_b + L_{seq}}$$
<div align="right">**Equation 4**</div>

Therefore, disability glare is greater for older observers, when the illuminance of the glare source is high, and when the angle of eccentricity is low. Disability glare as formulated does not seem to have a spectral dependence (Simunovic, 2012).

Discomfort glare, on the other hand, has a spectral component. For example, one study found that the discomfort glare caused by a blue monochromatic source (480 nanometers) was approximately two times the discomfort glare caused by a 550-nanometer monochromatic source at similar luminance levels (Flannagan et al., 1989). However, in order to have similar luminance, the irradiance of the blue source had to be approximately seven times the irradiance of the 550-nanometer source. This is because the human eye is less sensitive to blue and red colors than green colors when there is enough light for the cones in the retina to function. This state is called photopic lighting and typically occurs above 3 candelas/meter^2 average luminance.

CHAPTER 2. EXPERIMENTAL DESIGN

A human subjects experiment was conducted on the Virginia Smart Road. Since glare affects the elderly more than younger drivers (Chrysler, Danielson, & Kirby, 1996), elderly participants were used for the evaluation. In addition, since pedestrians are the most vulnerable population on roads at night, they were used as detection objects to evaluate the effectiveness of the approach. It is estimated that pedestrians are between 3 and 6.75 times more vulnerable in the dark than in daylight (Sullivan & Flannigan, 1999).

The current study examined the visibility benefits afforded by a cooperative headlighting concept. The scenario simulated was that of two vehicles meeting on an unlit, two-lane rural road. There were two parts to the experiment: static (neither vehicle was moving) and semi-dynamic (the participant vehicle was moving). The static and semi-dynamic portions were analyzed separately.

The static experiment had a two-factor (Separation Distance $\times$ 5 and Headlamp Configuration $\times$ 3) mixed-factors design. The semi-dynamic experiment had a three-factor (Headlamp Configuration $\times$ 2, Pedestrian Location $\times$ 4, and Direction $\times$ 2) mixed-factors design. Table 1 and Table 2 list each of the factor levels for each portion of the experiment.

Table 1. Factor and levels for static experiment.

Factor	Headlamp Configuration	Separation Distance Between the Two Vehicles (m)
	Conventional	100
	4U Stage I	75
Levels	4U Stage II	50
		25
		None

Table 2. Factor and levels for semi-dynamic experiment.

Factor	Headlamp Configuration	Pedestrian Location	Direction
	Conventional	1	Uphill (Up)
	4U (Stage I + II)	2	Downhill (Down)
Levels	No Glare	3	
		4	

INDEPENDENT VARIABLES

Several variables were manipulated or controlled during the study. They are listed below.

Between-Subjects Variables

- Gender (2 levels): Female, Male. This variable was chosen in order to generalize the results of both experiments to a broad driver population but was not used in the analysis.

Static Experiment Within-Subjects Variables

- Headlamp Configuration (3 levels): Conventional, 4U Lighting Stage I, and 4U Lighting Stage II. This variable was chosen to determine how the alternative headlighting scheme affects visibility. 4U Lighting goes through two stages as the two vehicles approach each other. In Stage I, the light on the side of each vehicle is turned on. In Stage II, the driver-side headlight is turned off while the side light and the passenger-side headlights remain on. As the vehicles pass each other, 4U Lighting reverts to conventional lighting.

- Separation Distance between the Vehicles (5 levels): 100 meters, 75 meters, 50 meters, 25 meters, and none. This was the separation distance between the headlights of both vehicles. This was chosen to assess how the 4U Lighting system performance changes as the vehicles approach each other.

Semi-Dynamic Experiment Within-Subjects Variables

- Direction (2 levels): Uphill (Up) and Downhill (Down). This variable is a side effect of using both the outbound and return trips on the Virginia Smart Road. The Virginia Smart Road is a 2.2-mile closed road with turnarounds at either end. The road has a 6% slope and different backgrounds on each side of the road. In order to maximize road usage, both directions were used for the semi-dynamic experiment and there can be an effect on the detection distance. This variable was used to control for this effect.

- Pedestrian Position (4 levels): Pedestrians were placed at four locations relative to the non-participant (static) vehicle. The positions utilized are shown in Figure 2. All measurements were relative to the front-most point of the static vehicle's headlight. Position 1 was located on the centerline 20 meters behind the static vehicle. Position 2 was located 20 meters in front of the static vehicle. Position 3 was located 7 meters behind the static vehicle, and Position 4 was positioned 45 meters behind the static vehicle. Positions 2, 3, and 4 were 0.5 meters from the white edge line on the right shoulder with respect to the dynamic vehicle with the participant.

  Pilot testing was used to determine the four positions for pedestrian presentation. Position 1 was chosen because a pedestrian at this location is very difficult to see with conventional headlights due to the glare. Positions 3 and 4 were chosen for the same reason: they are hard to see due to glare from the oncoming vehicle. However, Position 4 was in the location that seemed to be the most helped by the 4U Lighting system, and Position 3 was chosen to be at a location where pedestrians were barely visible to the investigators with the 4U Lighting system in operation. Finally, Position 2 was set in front of the glare vehicle to measure whether or not the 4U Lighting system performed worse than conventional headlights.

  There was a small area between the two vehicles on the centerline that was of interest to include in the study (shown in the blue rectangle in Figure 2). During static piloting, there did not seem to be either a detriment or improvement to visual performance utilizing the 4U Lighting system because of the strong negative contrast provided by the glare vehicle headlamp(s). This area was, however, deemed too risky to test semi-dynamically with

pedestrians as there was no escape route should the participant vehicle lose control. Using pedestrian mannequins as an alternative was not within the scope of the project.

- Headlamp Configuration (2+ levels): Conventional and 4U Lighting. This variable was chosen to determine how the alternative headlighting scheme affects visibility. The experiment was balanced with respect to these two levels. In addition, a No Glare condition was presented for Pedestrian Position 3 only for comparison of the detection distances. In the No Glare condition, the glare vehicle was not present in the test section and not visible to the participant.

Figure 2. Illustration. Semi-dynamic experiment setup with pedestrian locations.

DEPENDENT VARIABLE

In both experiments, detection distance of a pedestrian was used to determine the difference in visual performance of the participant afforded between 4U Lighting and conventional headlighting. The pedestrian visibility distance was measured by differing approaches in the static and dynamic experiments. In both experiments the measurements were reported in meters.

- Pedestrian Visibility Distance: The static experiment utilized the "method of limits" approach to establish thresholds and to record the distance when participants could see the pedestrian under each lighting condition. The participant would honk the vehicle horn when they were certain they could see the pedestrian again after the pedestrian moved out of visible range of the participant. The distance on the roadway between the participant's eyes and the location of the pedestrian was measured manually using a measurement

wheel. Since the pedestrians were moving at walking speed, the term "detection distance" was not as descriptive as "visibility distance."

- Pedestrian Detection Distance: During the dynamic experiment, the pedestrian detection distance was measured by differential Global Positioning Systems (DGPS) and converted into meters along the roadway between the participant's eyes and the pedestrian. The pedestrian positions were measure by the DGPS systems relative to the glare vehicle for each trial. The vehicles included an onboard data collection system that recorded audio, participant video, and button presses by the in-vehicle experimenter. When the participant verbally indicated that they were sure they saw a pedestrian, the in-vehicle experimenter pressed the button to mark the data. In data reduction, the reductionists would find the moment of each button press and go back a few seconds in the video and audio in order to find the moment when the participant is just starting to speak. The DGPS location of the vehicle was taken from that moment to remove the reaction time of the in-vehicle experimenter.

EQUIPMENT AND FACILITIES

Smart Road

The experiment was conducted on the Virginia Smart Road. The Smart Road is a 2.2-mile long, two-lane, restricted-access road. The test area was located on the ¾-mile straight section between the bridge and Turn 2 as shown in Figure 3. The participants drove loops from Turn 2 to the Bottom Turn and back to Turn 2.
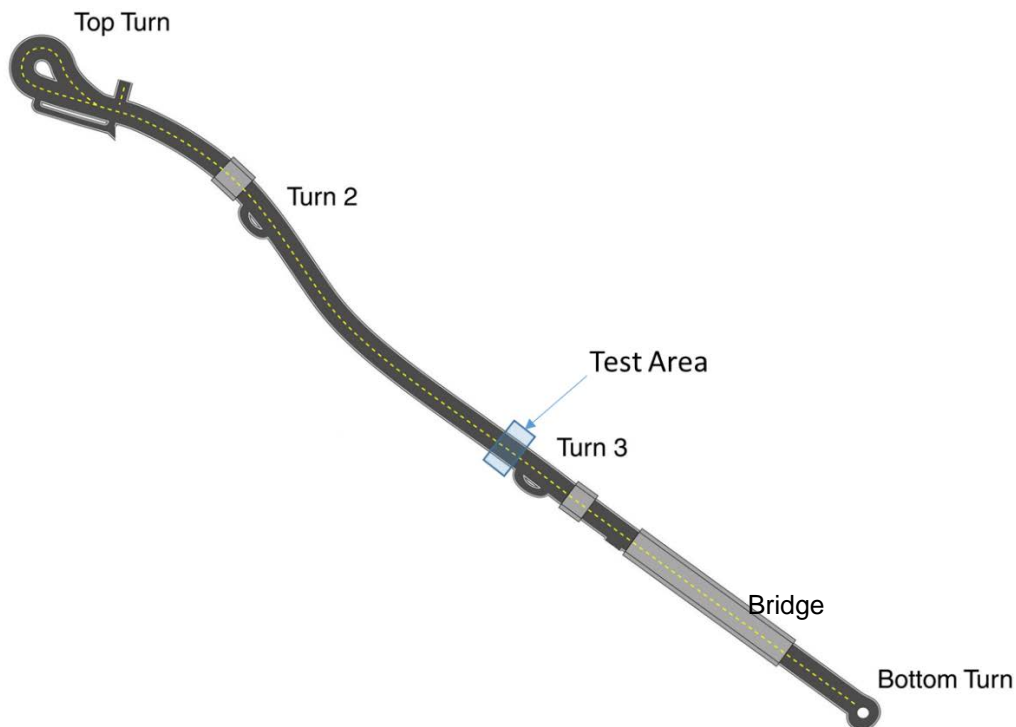

Figure 3. Illustration. The Virginia Smart Road.

Test Vehicles

The experiment used two Ford Explorers (model years 1999 and 2000), each equipped with a data acquisition system (DAS). The DAS recorded camera views inside and outside the vehicle, as well as vehicle speed, Global Positioning System (GPS) location, and other data from the vehicle's network. The DAS system also records audio in the vehicle and has a button for marking the data that can be pressed by the in-vehicle experimenter. The vehicles were fitted with DGPS for high-accuracy location measurement (± 0.1 meters typically), vehicle-to-vehicle (V2V) communication equipment, and a custom headlight/4U Lighting control system. The 4U Lighting control system automated the lighting control based on the relative positions of the two vehicles.

Headlamps and 4U Lighting Lamps

The experimental vehicles were equipped with two sets of U.S. street-legal, low-beam headlights (Figure 4), 90 millimeters in diameter. The upper set consisted of high-intensity discharge (HID) headlamps, and the lower set consisted of halogen incandescent headlights. Only the lower, incandescent headlights were utilized.

The 4U lighting was provided by an additional fifth headlight identical to those used on the front of the vehicle, attached to an arm extending a small distance from the headlamps on the driver's side of the vehicle and aimed counter to the vehicle's direction of travel to provide lighting for the other vehicle. The 4U headlamp was aimed 8 degrees away from the centerline of the vehicle in the horizontal and 1 degree upward to optimize the lighting for the other vehicle.

The headlights were aligned to Society of Automotive Engineering (SAE) standards on a regular schedule during the experiment.

Figure 4. Photo. One of the experimental vehicles.

4U Lighting Control and Operation

To address the reduction in visibility (disability glare) when there is an oncoming vehicle without beam shaping of the headlights, either the luminance of the glare source needs to be reduced, the luminance of the observed object needs to increase, or the eccentricity needs to be increased. The 4U Lighting concept addresses all three.

The main idea of the 4U concept is to control the headlight beam to shine light to the side and rear area of the car for the benefit of the oncoming car. This increases the luminance of any object on or in the road that would be affected by the veiling luminance from the headlights of the opposing vehicle.

In addition to adding light to the side of the vehicle, during discussions at the Virginia Tech Transportation Institute (VTTI) it was proposed to turn off the driver side headlight as the two vehicles passed each other. The rationale behind this proposal is the fact that the driver side headlamp creates much more glare than the passenger side headlight. Based on the International Commission on Illumination (CIE) formula for a distance of 50 to 100 meters, the driver side headlight causes five times more veiling luminance than the passenger side headlight. Dimming the driver side headlight thus reduces both the luminance and increases the eccentricity of the combination of the two headlights on the opposing vehicle.

The approach used for the experiment was a simplified version of the 4U Lighting concept shown in Figure 1. The 4U Lighting system tested had discrete stages as opposed to continuously variable light outputs. These stages are described in Table 3 along with the separation distances used. The lights were only utilized in one of two states, on or off; however, a 0.5-second ramp up and down were used to prevent participants from being startled or distracted by the transitions. These distance values were determined through careful pre-pilot testing and a literature review.

Table 3. 4U Lighting stages for this study.

Stage	Description	Separation Distance
4U Lighting Stage 0	Both conventional headlights on	> 100 meters
4U Lighting Stage I	Both conventional headlights on and the side light turned on	100–50 meters
4U Lighting Stage II	Passenger side headlight on, side light on, driver side headlight off	50–12 meters
4U Lighting Stage 0	Both conventional headlights on	< 12 meters

The 4U Lighting control system was composed of multiple high-stability power supplies, computer-controlled relays, a laptop computer, and V2V communication, all off-the-shelf. The high-stability power supplies controlled the output of the headlamps. All of the power supplies were set to 13.5 ± 0.1 volts (typical alternator output) and remained within 0.1 volts for the entire experiment.

The V2V equipment used was from Savari and broadcast Basic Safety Messages (BSMs) using Dedicated Short Range Communication (DSRC) protocol. A BSM includes information needed to prevent collisions and is well-suited to determining the relative location and heading between two vehicles. However, the 4U system only needs to know the relative positioning of the two

vehicles and the heading. Since the activation distances were shorter than 200 meters, other sensors, such as forward collision radar, could be used to trigger the system at the appropriate distances.

A laptop with custom software was used to fully automate the 4U headlighting controls based on the relative location of the two vehicles. The laptop read the BSM from the V2V communication network and calculated the vehicles' separation and headings. The in-vehicle DAS also calculated and recorded the separation distance using the BSM in addition to more precise measurement of absolute position from DGPS.

The laptop software was programmed to turn on the 4U side light on both vehicles at a separation distance of 100 meters, turn off the driver side headlight at 50 meters, and then return to conventional headlighting at 12 meters of separation. These values could be adjusted in the software but were not changed during the course of the experiment. The software also had manual overrides for controlling the lighting during the static experiment.

Data Collection

The data were collected by hand for the static testing but automatically by the DAS during the semi-dynamic experiment. For the static test, the distances for pedestrian visibility were measured with an off-the-shelf measurement wheel.

During the semi-dynamic testing, the DAS collected BSM, DGPS, in-car video and audio, and button presses continuously. The latter were used by the in-vehicle experimenter to mark the data for later reduction when the participant indicated a pedestrian had been detected. All data were stored on solid state drives and uploaded to a network database for analysis.

To increase the relevance of the pedestrian detection distance measurement to real-world situations, the participant was told to drive the vehicle at a constant speed of 56 km/h (35 mph) without use of the cruise control during the semi-dynamic phase. An in-vehicle experimenter rode in the passenger seat and operated a button for marking the data.

The participant was told a pedestrian could appear on either side of the road and at varying distances from the glare vehicle, or might not be present at all. The pedestrian was then told to say "pedestrian" when they were sure they could see a pedestrian, at which point the in-vehicle experimenter pressed a button connected to the data collection system. This ensured that the participant remained in control of the vehicle and did not have to take their eyes off the road. To remove the in-vehicle experimenter's reaction time, the video and audio collected were used to identify when the participant first started saying "pedestrian" and the DGPS coordinates from that time were collected for the analysis. The DGPS coordinates of both vehicles and the relative position of the pedestrian locations relative to the vehicle were used to calculate the pedestrian detection distance in meters.

Pedestrian Clothing

To eliminate color as a variable, the pedestrians were dressed in uniformly gray garments. Figure 5 shows the pedestrian in profile and the gray garments worn. 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 6. The integrals of the reflectance for the clothing, calculated between 360 and 800 nanometers using the trapezoid rule and weighted for the eye's spectral sensitivity, are listed in Table 4. 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).

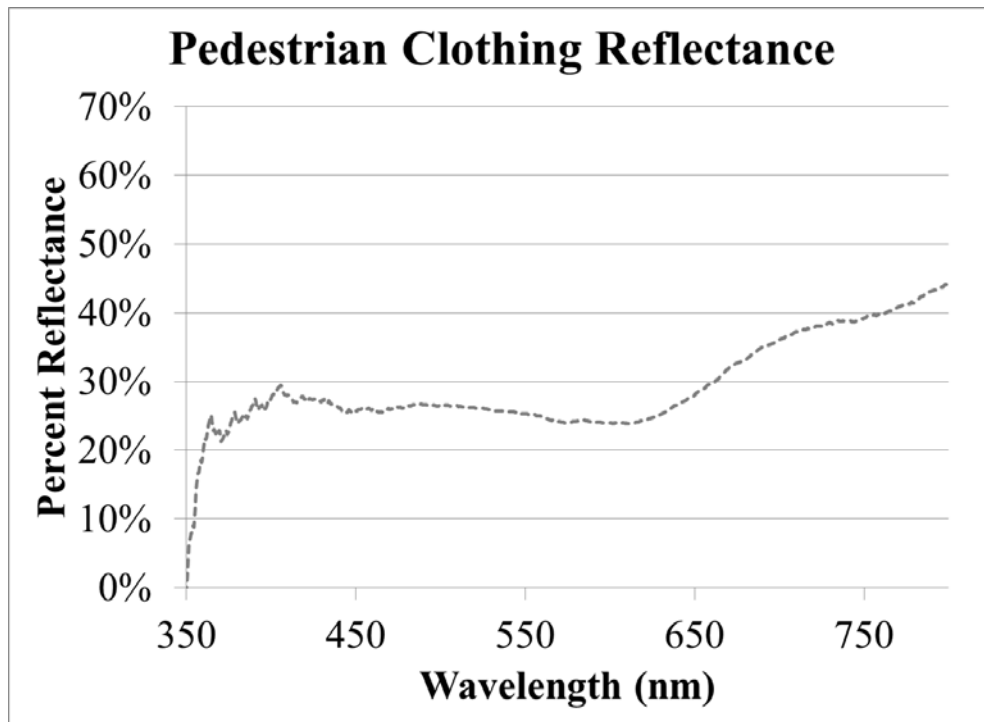**Figure 5. Photo. A confederate pedestrian in profile in gray clothing.**

Figure 6. Graph. Pedestrian clothing reflectance.

Table 4. Integral of pedestrian clothing reflectance.

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

EXPERIMENTAL PROCEDURE

Participant Recruitment, Consent, and Compensation

Recruitment was performed via the VTTI participant database and word of mouth. A general description of the study was provided to the participants over the phone before they decided if they were willing to participate. If they were interested, participants were then screened with a verbal questionnaire to determine whether they were licensed drivers and whether they had any health concerns that would exclude them from the study. Demographic information was collected, and participants were asked about their experience driving at night. Eligible participants were scheduled to come to VTTI to participate and emailed a copy of the informed consent form. Upon arriving at VTTI, participants were taken to a conference room, where they were given a physical copy of the informed consent form and asked to read and sign the form. An experimenter offered to answer any questions that participants may have had about the consent form. Participants were paid $30 per hour of participation.

Participants

A total of 12 participants completed the study. Six older males and six older females participated. Drivers met the following criteria:

1. Must have a valid driver's license.

2. Must be a U.S. citizen or hold a green card and be willing to complete a W-9 tax form, which includes providing their Social Security Number.

3. Must be 65 and older.

4. Must not have more than two moving violations in the past three years.

5. Must have normal (or corrected-to-normal) hearing and vision.

6. Must be able to drive an automatic transmission vehicle without assistive devices.

7. Must not have caused an injurious accident in the past three years.

8. Must drive at least two times per week.

9. Cannot have lingering effects of heart condition, brain damage from stroke, tumor, head injury, recent concussion, or infection. Cannot have had epileptic seizures within 12 months, uncontrolled current respiratory disorders or require oxygen, motion sickness, inner ear problems, dizziness, vertigo, balance problems, uncontrolled diabetes for which insulin is required, chronic migraine, or tension headaches.

10. Must not have a history of eye injury or eye surgery.

11. Cannot currently be taking any substances that may interfere with driving ability, cause drowsiness, or impair motor abilities.

The participant's vision was tested and averages are shown below along with the average age.

Table 5. Participant average age and average vision test results.

Age	Visual Acuity (Both)	Low Contrast Visual Acuity (Both)	Mesopic Vision Filter (Both)
67.0	24.8	32.2	34.9

Experimental Protocol

When participants arrived for participation, they were escorted to a conference room, where they read and signed the informed consent form, performed some simple vision tests, and completed paperwork. Participants were then read a script describing the tasks they would perform before being escorted to the experimental vehicle. Participants were accompanied by an in-vehicle experimenter for the full duration of the testing.

The testing protocol consisted of an initial exposure to the 4U Lighting system, a static test, and a semi-dynamic test.

Initial Exposure

The testing began by introducing the participants to the 4U Lighting system through an impression lap. The participants were not given details about the operation of the 4U Lighting system other than that it was a headlight experiment. During the impression lap, the participant drove past the other vehicle ("glare vehicle") with both traveling at 56 km/h (35 mph) with no assigned tasks other than operating the vehicle. For the first pass, both vehicles used conventional headlighting. On the second pass, both used the 4U Lighting system (Figure 7). After the second pass, the participants were instructed to stop in Turn 2 and asked three questions to get their first impressions. The questions were intended only to determine how noticeable the system was and to get an idea of public acceptance. They were asked:

1. Did you notice anything on the second pass of the other vehicle?
2. Do you think you could see farther the second time?
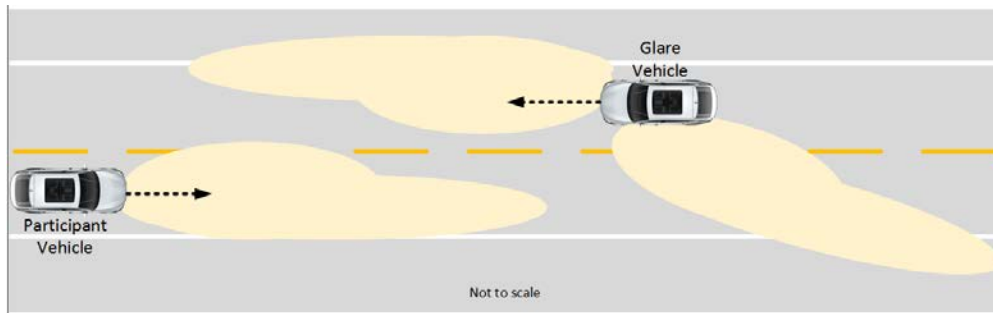3. Did you find the lighting less glaring?

Figure 7. Illustration. Impression lap. During the impression lap, the participant drove past the glare vehicle with both traveling at 56 km/h (35 mph). For the first pass, both vehicles used conventional headlighting. On the second pass, both used the 4U Lighting system. After the second pass, the participants were asked three questions to get their first impressions. *Static Test*

The static test was performed next. The first part of the static test was a pedestrian detection task using Stage I of the 4U Lighting system (both conventional headlights and the side light). One pedestrian was positioned on the road on the centerline and a second was positioned 0.5 meters from the shoulder on the participant's side of the road. The glare vehicle was parked in the opposite lane, facing the participant vehicle at distances between 100 and 25 meters of separation. In order to save time, the pedestrians moved in unison, walking parallel paths approximately the same distance from the participant car. Participants were instructed to watch the pedestrians as they walked away from the participant vehicle and to honk the horn when they were certain that they could no longer see one of them. They were then asked which pedestrian was no longer visible. After that, the pedestrians walked back toward the participant vehicle and the participant was asked to honk the horn when they could see that pedestrian again. On the second honk, the pedestrians stopped moving and the distance between the participant car headlights and the identified pedestrian was measured (Figure 8). The in-vehicle experimenter recorded this data. This process was then repeated for the other pedestrian.

After the limits of visibility were determined for both pedestrians for the 4U Lighting Stage I condition, the conventional lighting condition was tested. In order to save time, the pedestrians did not reset near the participant car but rather walked up the hill toward the participant, who was instructed to honk the horn when they were certain they could see one of the pedestrians. That distance was measured and recorded, then the process was repeated for the other pedestrian. These steps were repeated until all separation distances and No Glare conditions were tested.

Both head lamp conditions were counterbalanced with all the vehicle separation distances with the exception of "No glare." No glare by definition means the glare vehicle is not present at all and, therefore, vehicle separation distance is not measurable.
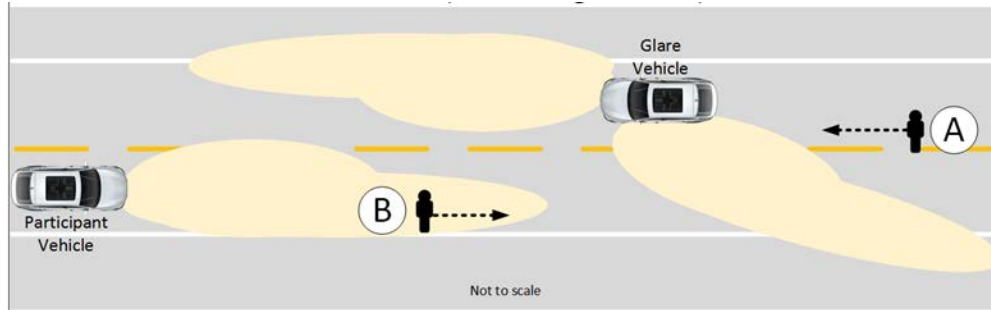
Figure 8. Illustration. Static test. Static Test A: The pedestrian walked toward the participant vehicle and the participant honked the horn when they became visible. Static Test B: The pedestrian walked away from the participant vehicle and the participant honked the horn when they became invisible. Then the pedestrian backed up until the participant honked again when they became visible.

Semi-dynamic Test

For the semi-dynamic testing, the participant was instructed to drive at 35 mph through the test zone while the second or "glare" vehicle remained stationary. Fixing the position of the glare vehicle allowed accurate placement of pedestrians relative to the meeting point of the two vehicles.

During the semi-dynamic event, the 4U Lighting system was active on both vehicles. The system would be placed into fully automatic 4U mode or conventional mode by the researcher before the start of each pass. The use of V2V communication, GPS positioning, and computer control ensured high repeatability of the distances for transition from one stage to the next for the 4U Lighting system.

Pedestrians were presented in the locations near the glare vehicle as illustrated in Figure 2. The lighting conditions were presented in one of four orders, differing only by the order in which the lighting conditions and pedestrian positions were presented. This task is illustrated for one condition in Figure 9.

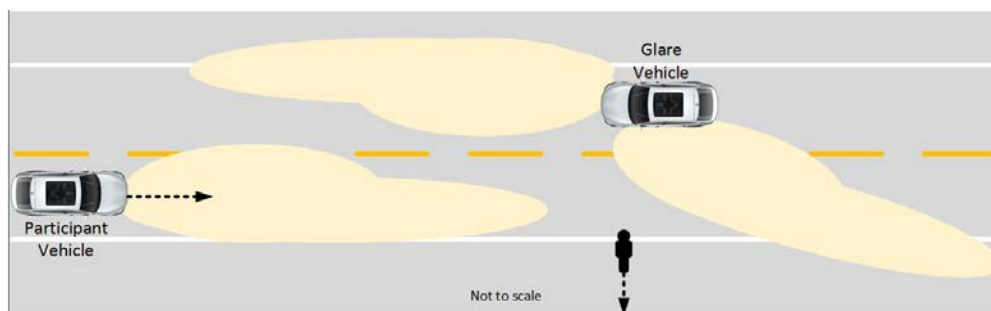**Figure 9. Illustration. Semi-dynamic test. The pedestrian stood in proximity of the glare vehicle (0.5 m outside the participant's lane) as the participant vehicle drove past it. The participant indicated when the pedestrian was visible and could be identified as a pedestrian. Once seen or when the vehicle was within ~25 m, the pedestrian "cleared" by walking away from the participant's lane.**

During the semi-dynamic testing the participants were instructed to vocalize "pedestrian" when they were sure it was a pedestrian they had detected. At the moment "pedestrian" was spoken, the in-vehicle experimenter pressed a button that was connected to and recorded by the vehicle data collection system in parallel with video and audio of the participant and positioning of the vehicle. In post-experiment data reduction, the buttons were used to locate the detections, but the video and audio were analyzed by human data reductionists to find the precise time when the participant started to say "pedestrian." This was done to remove the in-vehicle experimenter's reaction from the measurement of the moving vehicle's position. The positioning of the pedestrian locations was measured during piloting and could be used with the positioning of the vehicle to measure the detection distance at the moment of detection by the participant.

CHAPTER 3. DATA ANALYSIS

The static test analysis was a simple comparative test of the means of the detection distances between the No Glare, Conventional, and 4U Lighting Stages. The static experiment was comprised of a reduced set of presentations due to project scope limitations and therefore statistical analysis was not attempted. Distances were measured by hand and recorded by the lead researcher by hand.

For the semi-dynamic experiment, a data reductionist viewed the video recorded by the DAS and verified each time a participant correctly detected a pedestrian. This timestamp was used to extract the vehicle's DGPS coordinates with an uncertainty of approximately ±1.5 meters. The pedestrian presentation positions were measured with DGPS to approximately ±0.5 meters. The detection distances were calculated from these two measures. Analyses of variance (ANOVAs) were conducted for the detection distance. Significance was determined with an alpha of 5%. For significant factors, Student-Newman-Keuls (SNK) and T-type post hoc tests were conducted to determine which factor levels were significantly different.

Finally, participant impressions were categorized and summarized. Participant impressions, since they were open ended, were characterized into three categories: positive, neutral, and negative for each question. Included in the neutral category would be any answers that were neither positive nor negative. Percentages were calculated for each question for each category to assess public acceptance, even if only for a subset of the population.

STATIC RESULTS

The static experiment was performed with pedestrians simultaneously on the centerline and on the right shoulder of the road relative to the participant. Data were collected on pedestrian visibility distances and the means were compared graphically. The presentation of the conditions was not balanced, making statistical analysis more complex than a balanced presentation. In addition, the static results were more intended to map out the upper bounds of the system and were of less interest to the project. Therefore, statistical analysis consisted of only calculating means and standard deviations. No statistical significance was calculated.

The advantages of the 4U Lighting approach for seeing pedestrians on or near the centerline are clearly seen in the plot of the mean pedestrian visibility distance versus head lighting type and vehicle separation distance shown in Figure 10. The mean visibility distance during the No Glare condition is shown as a line of constant value with a single mean data point at a separation of 0 meters (no oncoming vehicle) for reference with error bars. The error bars represent the standard error for each point shown in the graph, which is the mean across all participants.

The visibility distance for conventional headlighting increases as the distance between the vehicles increases beyond 50 meters and exceeds the visibility distance of the No Glare condition (74 meters) at a separation distance of approximately 83 meters. At first this appears counterintuitive, but the pedestrian is 10 meters in front of the glare vehicle and is in negative contrast, which means that headlights from the glare vehicle are providing the visibility. At 50 meters and 25 meters of separation, the visibility distance is longer than the separation distance, meaning that the participant's headlights are primarily responsible for the visibility.

The visibility distance of the pedestrian on the centerline is improved by a nearly constant 35 meters during 4U Lighting Stage I and jumps up to a 50-meter improvement in visibility for 4U Lighting Stage II (driver side headlight off). While not tested, it appears from the data trend that the Stage I improvement would continue to a vehicle separation of 0 meters and would likely be more than the No Glare visibility distance.

The Stage II improvement over Stage I at 50 meters is 14 meters of additional visibility distance. It appears that Stage II could be initialized at a larger separation distance between the two vehicles. The Stage II 4U Lighting improvement in pedestrian visibility distance over conventional head lighting is 47 meters at a vehicle separation of 25 meters, suggesting that there are diminishing returns as the vehicles get closer. However, there are insufficient data to extrapolate the trends in either direction.
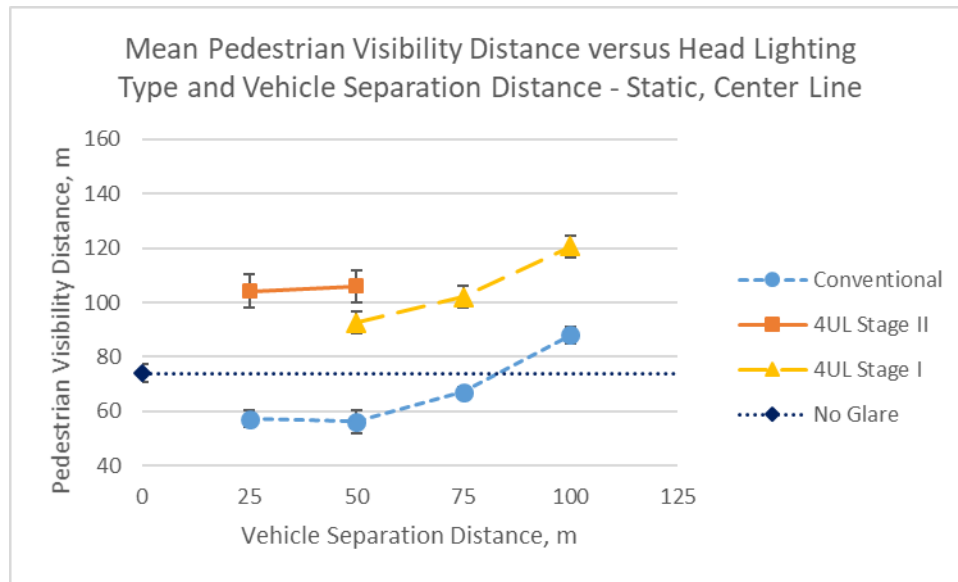

Figure 10. Graph. Mean pedestrian visibility distance versus headlamp type and vehicle separation distance for a pedestrian on the centerline, static test (Location A). The error bars represent the standard error. 4U Lighting is abbreviated to 4UL in the legend.

The improvement in mean pedestrian visibility on the right shoulder is plotted in Figure 11 relative to the vehicle separation distance and headlighting type. Again, the No Glare condition is shown for reference.

As can be seen, the pedestrian visibility distance on the shoulder versus conventional headlights did not change much with separation of the vehicles and is always lower than the visibility distance for the No Glare condition and is different from the visibility distances for the pedestrian on the center line. In addition, the No Glare visibility distance is longer at 85 meters versus 74 meters for the centerline pedestrian position.

This is because of the larger lateral separation of the pedestrian from the glare vehicle headlights: the veiling luminance was lower and the participant vehicle was providing nearly all the illumination at all positions. The reason visibility distance does not exceed the No Glare

condition for pedestrians on the shoulder is due to the participants not getting any benefit of negative contrast from the glare vehicle headlights. The disability glare from the glare headlights reduced the visibility distance between 4 and 9 meters versus the No Glare condition, with the worst reduction occurring at the 75-meter separation distance, where the visibility distance was 76 meters, barely in front of the glare vehicle.

The 4U lighting provided a large benefit in visibility distances for pedestrian on the shoulders. The 4U lighting benefit for the pedestrian on the shoulder is similar to the benefit for the visibility distance of the pedestrian on the centerline but with an additional 20 meters in visibility distance. The pedestrian visibility is dependent on vehicle separation, as expected, because the 4U Lighting system travels with the vehicles. The benefit is 60 meters (75%) at a 100-meter vehicle separation and tapers to a benefit of 40 meters (50%) by the 50-meter vehicle separation distance. The visibility distance is increased by 5 meters with the switch to Stage II but then the downward trend continues.
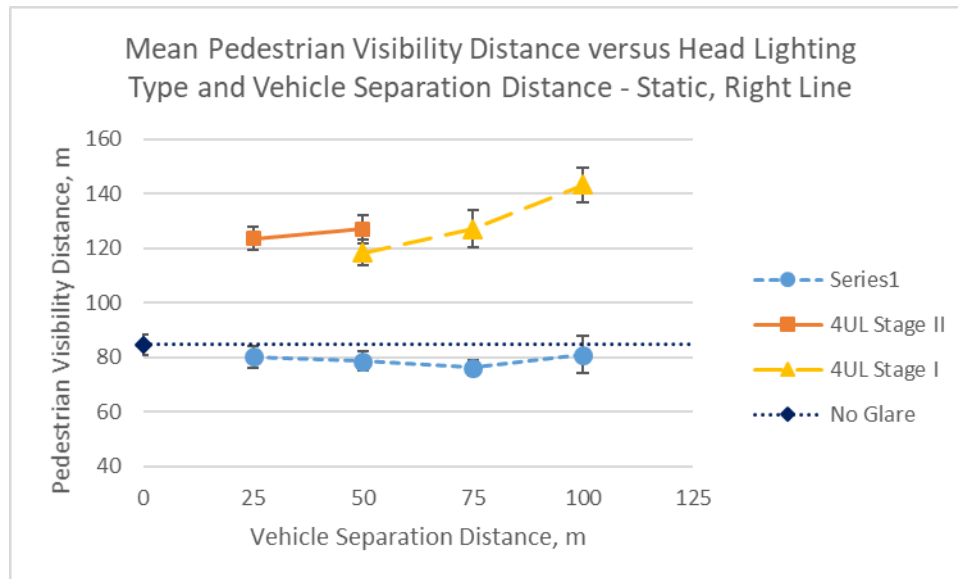

Figure 11. Graph. Mean pedestrian visibility distance versus headlamp type and vehicle separation distance for a pedestrian on the shoulder, static (location B). The error bars represent the standard error. 4U Lighting is abbreviated to 4UL in the legend.

SEMI-DYNAMIC RESULTS

In the semi-dynamic test, the participant vehicle was moving while the glare vehicle remained stationary. A pedestrian detection task was used to compare 4U and conventional lighting.

Table 6 shows the ANOVA results for the visibility distance of Headlamps (2) * Pedestrian_Location (4) * Direction (2). All factors were significant ($p < 0.05$), as well as the interactions of Headlamps*Pedestrian_Location and Pedestrian_Location*Direction, proving that the 4U Lighting system correlates with the improved detection distances over conventional headlamps for the selected pedestrian locations. The interaction of Headlamps*Direction and the third-order interaction (Headlamps*Pedestrian_Location*Direction) were not statistically

significant. The significance of direction was expected because of the difference in the background and the difference in the attitude of the vehicle going downhill versus uphill. This has been seen in many detection distance studies performed on the Smart Road. The significance of detection distance versus pedestrian location was also expected due to the positioning of the pedestrians at various positions around the static vehicle. The interaction of pedestrian location and direction was also expected. The non-significance of the interaction of headlamps and direction shows that the 4U Lighting headlights give the same advantage no matter the direction.

Figure 12 shows that the 4U Lighting technology gives vehicle operators a mean advantage in detection of a pedestrian of 19 meters over conventional headlighting at 56 kilometers per hour (15.56 m/s, 35 mph). This is a 23% improvement in detection distance and equates to a 1.2-second advantage in spotting a pedestrian conflict using the 4U Lighting system over conventional lighting. The pairwise analysis using SNK and *T*-tests confirmed that this difference is significant.

Table 6. ANOVA results for pedestrian detection distance.

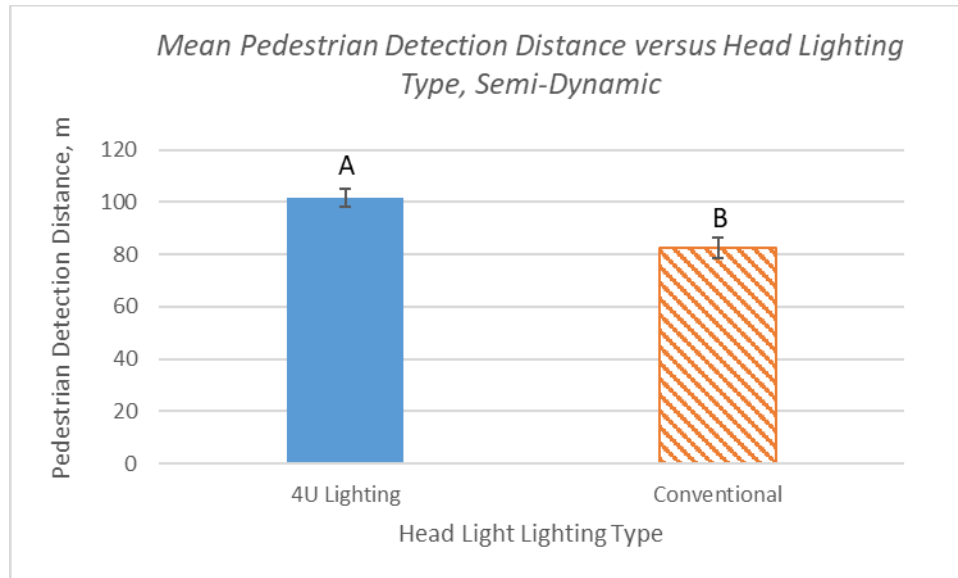| Source	DF	Type III SS	Mean Square	*F* Value	Pr > *F*
Headlamps	1	6869.8	6869.78057	34.73	<.0001
Pedestrian_Location	3	16724.7	5574.90021	28.19	<.0001
Headlamps*Pedestrian_Location	3	4296.9	1432.30334	7.24	0.0002
Direction	1	15430.7	15430.68131	78.02	<.0001
Headlamps*Direction	1	760.2	760.16211	3.84	0.0534
Pedestrian_Location*Direction	3	4638.4	1546.12136	7.82	0.0001
Headlamps*Pedestrian_Location*Direction	3	338.5	112.84798	0.57	0.6360

Figure 12. Chart. Mean pedestrian detection distance versus lighting type.

The error bars represent the standard error. Means with the same letter are not significantly different.

The 4U Lighting system has a different advantage for each pedestrian location. Figure 13 shows the mean pedestrian detection distances for each combination of pedestrian location and head lighting type along with the mean for the No Glare condition for comparison. The No Glare condition was only presented at Position 3. Figure 13 also shows that the mean detection distances for conventional lighting at Position 1 and the 4U Lighting at Position 4 were significantly different from all of the other mean detection distances presented as indicated by the letter labels. The No Glare condition was not included in the pairwise comparison, but a separate subanalysis of just Position 3 found that the mean detection distances for the three lighting types were not statistically different from each other.

The 4U Lighting system increases the pedestrian detection distance at Position 1 by 26 meters and at Position 4 by 38 meters, each of which is statistically significant by pairwise analysis. Analysis of the detection distance means by pedestrian location also shows statistical significance for Position 1 and 4 but not for Positions 2 and 3.

There were smaller increases in performance at Positions 2 and 3 of 10 meters and 3 meters, respectively, although pairwise comparison indicates those are not statistically significant. Recall that Position 1 was on the centerline 20 meters behind the glare vehicle's headlight and Position 4 was at the edge of the road 45 meters behind the glare vehicle. Both positions were chosen to highlight the performance of the 4U Lighting system. Also, Position 3 was chosen to be in a location that was not well lit by the 4U Lighting condition, which was confirmed by the analysis.
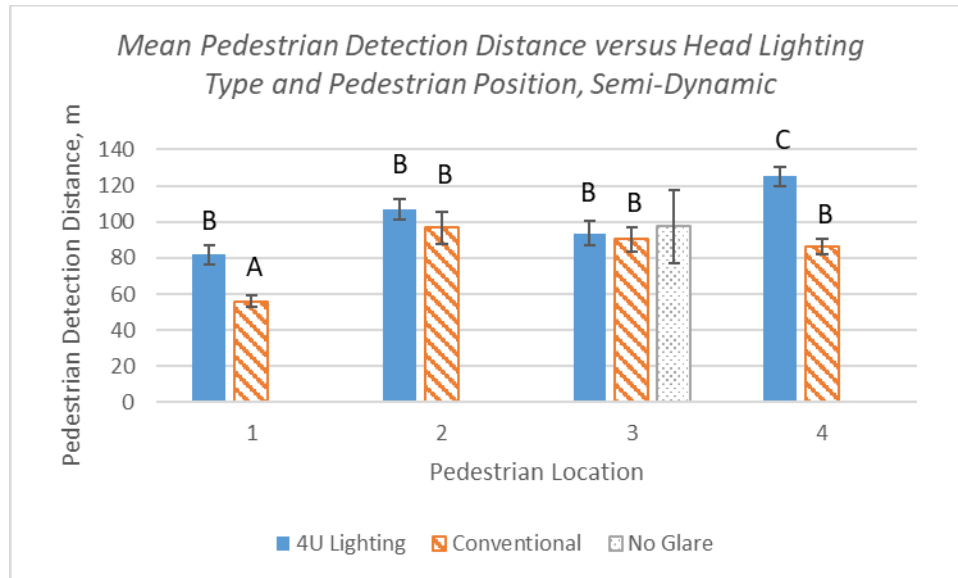
Figure 13. Chart. Mean pedestrian detection distances for each position versus lighting type. The error bars represent the standard error. Means with the same letter are not significantly different. The No Glare mean is shown for comparison only and was not included in the pairwise post hoc analysis due to the imbalance in presentation of the No Glare condition.

The 4U system enabled drivers to detect a pedestrian at Position 3 in the presence of the glare vehicle just as well as when there was no opposing vehicle ("no glare"). The 4U Lighting system did not make it harder to see the pedestrians for any of these locations, including Position 2, which was selected to be in front of the glare vehicle and thus not lighted by the 4U Lighting system. This is a very strong result.

CHAPTER 4. DISCUSSION

This initial test of the 4U Lighting system strongly support the hypothesis: that oncoming headlight glare can be reduced by an innovative cooperative headlighting scheme and pedestrian visibility can be improved for the vehicle operator. In addition, at least in specific cases (i.e., position 3), the 4U Lighting system enabled the participants to detect pedestrians as far as they could with no glare vehicle present.

STATIC TESTING

The static testing showed that the 4U Lighting system, which turned off the driver side light, improved pedestrian visibility on both the centerline and on the shoulder by more than 10 meters. The tested turn-off distance seemed to be a good choice and offered additional visibility distance for both pedestrian locations. Finally, the static data indicated improved visibility of both pedestrian locations over the No Glare condition.

The static testing also demonstrates that there is benefit when only one of the vehicles has the 4U Lighting system. The participant's vehicle did not provide any additional lighting. To the participant, this is identical to the situation where the oncoming vehicle is the only one equipped with the 4U Lighting system. The static testing showed no decrease in participant visual performance. Therefore, the testing showed the benefit of utilizing the 4U Lighting system before it is implemented on all vehicles.

SEMI-DYNAMIC TESTING

The semi-dynamic testing reinforced the static testing findings, but to a lesser degree. This is not uncommon in experimental studies and is due to the vehicle motion and participant attention needed to control the vehicle. The static testing showed an approximately 57% improvement in the visibility of the pedestrians. The semi-dynamic testing showed a lesser improvement of 23% over all pedestrian test positions and conditions. Positions 1 and 4 were improved significantly more: by 46% and 44%, respectively. This was expected since those were the two positions hardest to see during the pilot and development testing. In addition, Position 4 was located on the shoulder in the middle of the 4U Lighting side-light beam and was expected to get the most improvement.

Position 1 was closest to the driver side headlight of the oncoming car and so was subject to the most disability glare due to the smaller angle. That pedestrian position, while 20 meters from the front of the headlights, was only 18 meters from the GPS location, and the 4U Lighting was set up to use the distance between the GPS positions. Therefore, 18 meters can be subtracted from the detection distance to determine what stage the 4U Lighting was in when the detection of the pedestrian at Position 1 occurred. During the 4U Lighting conditions, the mean detection at Position 1 occurred at a separation distance of 64 meters, before the driver side headlight was turned off. This is an interesting finding, as it means that the lighting system would improve visibility for Position 1 even if the driver side light did not turn off. Similarly, the separation distance for the average detection distance for Position 4 was approximately 82 meters, meaning that the 4U Lighting system had not turned off the driver side light. The pedestrian positions

used were not optimized for testing the benefit of turning off the driver side headlight. However, the static testing showed that there was benefit.

For Position 2, the same adjustment shows that the separation distance was 128 meters and, therefore, occurred before the activation of the 4U Lighting system, negating that result. The detections at Position 3 occurred at 89 meters, and therefore followed the activation of the 4U Lighting in Stage I, which strengthens the finding that the 4U Lighting system did not worsen visibility or detection distance.

READINESS FOR IMPLEMENTATION

The 4U Lighting system used an off-the-shelf technology and could be implemented immediately. Many modern vehicles are already capable of incorporating a 4U lighting algorithm via their automatic headlight high-beam control.

The addition of a side light would be relatively low cost and could be integrated into the headlight. Additional lighting control hardware would be needed but could be as simple as an inexpensive relay.

Finally, connected or V2V technology is not required for the system to operate. Many vehicles already have a forward collision radar or LIDAR system that allow the measurement of the separation and relative speed between the vehicles, Even when only one vehicle is equipped with the system, sufficient information is provided to benefit the driver of the unequipped vehicle, thereby improving overall traffic safety.

CHAPTER 5. CONCLUSIONS

This project showed the effectiveness of an alternative cooperative highlighting method, dubbed "4U Lighting." This project also showed that the enabling technology and off-the-shelf components currently exist to achieve the approach and reduce glare. The system relied on V2V technology for sensing the relative positions and headings of the two vehicles, but since the activation distances were shorter than 200 meters, other sensors, such as radar used for forward collision warning, could be used to activate the system at the appropriate distances.

Cooperative headlighting significantly improves the visibility of pedestrians for the population over 65 years old.

- During testing, the 4U Lighting system did not make it harder to see any pedestrian position tested relative to conventional lighting.

- The 4U Lighting system improved driver visual performance 20 meters behind the glare vehicle on the centerline (i.e., position 1) by 26 meters, which is a 46% improvement in visibility.

- The 4U Lighting system improved driver visual performance at 45 meters behind the glare vehicle on the shoulder (i.e., position 4) by 38 meters, which is a 44% improvement in visibility.

- The average improvement in pedestrian visibility was 57% or greater for the static test for pedestrians on the roadway shoulder and on the centerline in front of the vehicles. This is higher than the improvement during the semi-dynamic testing when the participant's attention was also on operating the vehicle.

- Stage I of the 4U Lighting system (side lighting) provided benefits without turning off the driver side headlight, showing that the system could provide benefits to the drivers even if only one vehicle was equipped with the system.

While these are extremely positive results, it is recommended that further research be conducted to fully characterize the safety improvements. A follow-on study should include additional factors such as:

- Both vehicles moving at a range of vehicle speeds;

- Pedestrian and targets at a wider range of locations around the two vehicles especially in the area ahead of the sidelight and behind the headlight of each vehicle;

- Various overhead lighting configurations;

- 4U Lighting parameter adjustments (turn-on and turn-off distances).

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