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**National Highway  
Traffic Safety  
Administration**



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September 2025

# **Lower Beam Headlighting System Performance On-Vehicle Test Procedure Examination**

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<b>16. Abstract</b> <p>The 2021 Infrastructure Investment and Jobs Act's Section 24212, <i>Headlamps</i>, required amending Federal Motor Vehicle Safety Standard No. 108 "to include performance-based standards for vehicle headlamp systems to ensure headlights are correctly aimed on the road" and "requiring those systems to be tested on-vehicle to account for headlight height and lighting performance." This report summarizes an effort to develop a candidate test procedure that assesses performance of lower beam headlighting systems while the headlamps are installed on the vehicle. A candidate test procedure for assessing headlighting system performance on-vehicle was developed based on an earlier NHTSA draft test procedure for assessing lower beam headlighting system performance and work by the University of Michigan Transportation Institute to assess a possible performance adaptation of FMVSS No. 108 test methods. Lower beam headlighting system performance was determined by turning on the lower beam headlamps as installed on a production vehicle and measuring the amount of light cast onto the forward roadway. Illuminance was measured over an array of specified locations that were determined by translating FMVSS No. 108 lower beam headlamp photometry test points from polar coordinates to lateral, longitudinal, and vertical test locations on a flat roadway.</p> <p>Seven light vehicles' lower beam headlighting systems were tested using the candidate on-vehicle measurement test procedure to document its accuracy and repeatability. The on-vehicle measured illuminance averaged 7 percent higher than illuminance values measured using existing lab-based methods. The difference between the illuminance measured in lab testing versus on-vehicle testing varied substantially with test vehicle and with measurement location. To assess the test procedure repeatability, the full test procedure was performed on a single vehicle five times. Results showed that measured illuminance values in close proximity to the cutoff line had the greatest variability. Overall, this work revealed the challenges of an on-vehicle measurement method compared to the existing lab-based method for assessing lower beam performance. The accuracy of the on-vehicle measurements was inferior compared to the lab-based measurements.</p>			
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## Acronyms and Abbreviations

ADB	adaptive driving beam
CV	coefficient of variation
FMVSS	Federal Motor Vehicle Safety Standard
IIHS	Insurance Institute for Highway Safety
IIJA	Infrastructure Investment and Jobs Act of 2021
ISO	International Standards Organization
OEM	original equipment manufacturer
SAE	SAE International, name changed from Society of Automotive Engineers in 2006
TRC	Transportation Research Center
UNECE	United Nations Economic Commission for Europe
UMTRI	University of Michigan Transportation Research Institute
VDA	vehicle dynamics area
VOA	visual optical aim
VOR	visual/optical - right

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## Executive Summary

The 2021 Infrastructure Investment and Jobs Act in Section 24212, titled *Headlamps*, (Infrastructure Investment and Jobs Act, 2021) tasked the National Highway Traffic Safety Administration with a rulemaking to amend Federal Motor Vehicle Safety Standard No. 108 “to include performance-based standards for vehicle headlamp systems to ensure headlights are correctly aimed on the road” and “requiring those systems to be tested on-vehicle to account for headlight height and lighting performance.”

This report summarizes research conducted to support NHTSA’s response to this mandate. The research performed sought to:

1. Develop a candidate headlighting system performance on-vehicle test;
2. Assess the candidate headlighting system performance on-vehicle test procedure by applying it to a set of light vehicles;
3. Study the accuracy of the candidate headlighting system performance on-vehicle test procedure by having the same headlamps tested in a photometric test lab. From the lab data, the expected illuminance at each of the candidate test procedure’s measurement locations were calculated. These values were compared to the on-vehicle measurement test procedure data to determine the accuracy of the candidate on-vehicle measurement method; and
4. Study the repeatability of the candidate headlighting system performance on-vehicle test procedure by testing a single vehicle several times.

Currently, headlighting system photometric performance for FMVSS No. 108 (49 CFR Sec. 571.108, 2024) compliance is measured at the equipment level. Single lamps are measured in a test lab using a goniometer, which measures the photometric intensity at test points specified in polar coordinates. To measure the on-vehicle performance of lower beam headlighting systems, a test method was developed by adapting methods used in previous NHTSA work that produced a draft lower beam headlighting system visibility confirmation test (Mazzae et al., 2019). In that testing, illuminance receptor heads were placed at test locations of differing lateral distance, longitudinal distance, and height from the front of a test vehicle to measure the intensity of light emitted by the lower beam headlamps.

For this effort the 2019 Mazzae et al. draft lower beam headlighting system visibility confirmation test method was used, but with modified measurement locations adapted to represent the FMVSS No. 108 lower beam headlamp photometric test points. Similar to work done by Flannagan and Sullivan (2011) using geometric transformations, the FMVSS No. 108 specified lower beam headlamp test point polar coordinates were turned into Cartesian coordinates located in the 80 by 15 foot test area in front of the vehicle at which the illuminance receptor heads were placed. Measurement locations varied for each vehicle based on the height of the optical center of the lower beam headlamps. Although on-vehicle testing measured both the driver-side and passenger-side headlamps simultaneously, one measurement location for each FMVSS No. 108 test point was used for both lamps.

To assess the candidate test procedure developed, seven light vehicles of model year (MY) 2019 or newer were measured. The test vehicles were horizontally aligned to the Cartesian coordinates of the test area designated for this effort.

Each lower beam headlamp was aimed to the vehicle manufacturer's specified vertical aim angle value specification. The headlamp not being aimed was occluded with a curtain. After both lower beam headlamps were adjusted, data was recorded from the illuminance receptor heads. Zero readings were also recorded by occluding both lamps with curtains.

After all on-vehicle headlighting system performance testing was completed, the headlamps were removed from the test vehicles and sent to an ISO-accredited photometric test lab to be measured. Testing of headlamps was performed to obtain FMVSS No. 108 lower beam headlamp photometry and ISO-candela scan data. The ISO-candela scans were used to extract values that corresponded to the measurement locations used in the on-vehicle testing. The lab-based results showed similar trends in illuminance variance as the on-vehicle test results.

On average, over all seven test vehicles and all measurement locations, the illuminance measured in the lab was 38.96 lux. Illuminance measured in the on-vehicle testing averaged 41.69 lux. On average, the on-vehicle measured illuminance was 7 percent higher than the laboratory measured illuminance, meaning that on average the on-vehicle test method measured illuminance higher than measuring the parts in a lab. The difference between the lab-measured illuminance and on-vehicle illuminance varied substantially across test vehicles.

There was a large relative difference between on-vehicle results and the lab testing results for many test vehicles and test point/subpoint combinations. The relative difference ranged from -311 percent to +80 percent. There was a large amount of variability in relative difference from test vehicle to test vehicle and from test point/subpoint to test point/subpoint. The average relative difference over all test vehicles and measurement locations was -35 percent. The absolute average relative difference, calculated over all test vehicles and measurement locations was 48 percent.

Repeatability testing of the lower beam headlamp performance on-vehicle test procedure was completed by performing five full test repetitions with a single test vehicle (the 2022 Toyota Camry). Analysis of the repeatability test data highlighted the sensitivity of measurements made near a lamp's cutoff line. Measurements showed that measurement locations at the vehicle manufacturer's target vertical aim angle (referred to "below as the horizontal line" points) had much higher coefficients of variation than test locations further from the target vertical aim angle.

Overall, this effort highlighted challenges associated with on-vehicle measurement as compared to lab-based measurement for headlighting systems performance testing. Although the two methods displayed similar trends, the accuracy of the on-vehicle measurements was inferior when compared to the lab-based measurements. This work also highlighted the complexity of precisely repeating test results for lower beam headlamp performance on-vehicle testing due to beam patterns' sensitivity to proper headlamp vertical aim. The inferior repeatability of the on-vehicle measurements seen during this research reveals the challenges associated with an on-vehicle measurement method as compared to a lab-based method for assessing lower beam performance.

## Introduction

### Background

The 2021 Infrastructure Investment and Jobs Act (IIJA) in Section 24212, titled *Headlamps*, tasked NHTSA with a rulemaking to amend FMVSS No. 108 to “include performance-based standards for vehicle headlamp systems” that address headlamp aim angle and measurement of lighting performance on-vehicle. Specifically, Section 24212 of the IIJA states:

- (b) RULEMAKING – Not later than 2 years after the date of enactment of this Act, the Secretary shall issue a final rule amending Standard 108—
  - (1) to include performance-based standards for vehicle headlamp systems—
    - (A) to ensure that headlights are correctly aimed on the road; and
    - (B) requiring those systems to be tested to account for headlight height and lighting performance on-vehicle.

This report summarizes research conducted to support NHTSA’s response to these requirements. The research performed sought to:

1. Develop a candidate lower beam headlighting system performance on-vehicle test.
2. Assess the candidate lower beam headlighting system performance on-vehicle test procedure by applying it to several light vehicles.
3. Study the accuracy of the candidate lower beam headlighting system performance on-vehicle test procedure by having the same headlamps tested in a photometric test lab. From the lab data, the expected illuminance at each of the candidate test procedure’s measurement were calculated. These values were compared to the on-vehicle measurement test procedure data to determine the accuracy of the candidate on-vehicle measurement method.
4. Study the repeatability of the candidate lower beam headlighting system performance on-vehicle test procedure by testing a single vehicle several times.

Photometric testing for automotive lighting has traditionally been lab-based, equipment-level testing. As described in FMVSS No. 108 and United Nations Economic Commission for Europe (UNECE) Regulation No. 149 (2023), lamps are tested individually, separate from the vehicle and regulated as such. Testing is performed using a goniometer, a device that holds the lamp in the on-vehicle orientation and rotates the lamp to each vertical and horizontal test angle. Required photometric test points, at which intensity is measured, are specified as polar coordinates (horizontal and vertical angles) with an origin at the photometric center of the lamp. The photometric intensity at a test point is measured by a fixed sensor located a distance away from the lamp. This distance can be changed based on the standard being tested and the capabilities of the test equipment.

Recently there have been increasing efforts to investigate on-vehicle test methods for automotive headlamps. The Insurance Institute for Highway Safety (n.d.) started testing headlighting system performance in 2016 via a dynamic test procedure that measures and rates the on-road illumination provided by these systems. The introduction of adaptive driving beam headlighting

systems that operate only when a vehicle is being driven above a certain speed by actively modifying the headlamp beam pattern to cast more illumination in areas of the roadway not occupied by other vehicles, while limiting illumination to lower beam levels in the direction of other vehicles, has necessitated new a new approach to headlighting system testing. Therefore, NHTSA performed research to develop a dynamic headlighting system performance on-vehicle test (Mazzae et al., 2022).

There are several key differences between lighting test procedures that are vehicle-based and existing equipment-level, lab-based test procedures. While lab-based testing usually involves a single lamp being tested at a time, vehicle-based, on-vehicle lamp testing could have two or more lamps active at a time. For example, performing on-vehicle testing of lower beam headlamps could involve both lower beam headlamps active as well as the front parking lamps on both sides. (FMVSS No. 108 requires parking lamps to be active when lower beam headlamps are active.) An important factor that is greatly diminished by lab-based testing is lamp positioning. Lab-based testing uses photometric test fixtures designed and made by OEMs that accurately position a single lamp of a specific model for lab testing. Although tools are available that aid in the positioning of vehicles, there remains an increased number of factors affecting measurement accuracy when compared to lab-based test fixtures.

## **Past Research**

To arrive at a feasible headlighting system performance on-vehicle test procedure, past work on measuring headlamp performance was reviewed. The following sections describe the past research most relevant to this effort. The first document provided a basis for measuring lower beam headlamp performance on-vehicle and the second document provided a basis for translating FMVSS No. 108 photometry test points to a roadway setting.

### ***Lower Beam Headlighting System Visibility Confirmation Test – Test Procedure Assessment (Mazzae et al., 2019)***

In 2019 NHTSA developed and published a draft test procedure (Mazzae et al.) for confirming the visibility performance of lower beam headlighting systems on a test track using a full vehicle. Headlighting system performance in this procedure was determined by activating the lower beam headlamps on a production vehicle and measuring the amount of light cast onto the forward roadway over an array of specified locations. Performance levels were calculated based on measured values for the specified measurement locations. These measurement locations either corresponded to locations for roadway visibility or driver glare for other vehicles. The roadway visibility locations were either at the right edge, left edge, or center of the lane, were at a height of 0.2 m, and ranged in longitudinal distance from 45 m to 115 m. The driver glare measurement locations were located laterally on the left lane edge, ranged in height from 1.0 m to 1.2 m, and were located at a longitudinal distance of 60 m.

Three vehicles were subjected to three repetitions (sets) of the test procedure. Results showed that measured values for visibility and glare measurement locations were consistent across the three test repetitions. Measurement results for an expanded array of measurement locations showed higher coefficient of variation values for the center and left lanes than were seen for the right lane. Performance levels based on the center- and left-lane locations were consistent across the three test repetitions for two vehicles but were not consistent for the third vehicle because one of the measured values was very close to the limit for inclusion in the net illuminance

calculation that was the basis for visibility scoring. The coefficient of variation for most test sets were 8 percent or less, indicating good repeatability.

The full vehicle-based test procedure was found to be effective in characterizing lower beam headlamp visibility performance levels and indicated good test repeatability. This test procedure was used as input to the testing described in this report.

### ***Feasibility of New Approaches for the Regulation of Motor Vehicle Lighting Performance (Flanagan & Sullivan, 2011)***

In 2011 NHTSA published a report documenting University of Michigan Transportation Research Institute research assessing the feasibility of a performance-based approach to vehicle lighting regulation, specifically for photometric requirements. Currently FMVSS No. 108 requires headlamp light intensity be measured in a lab at specified photometric test points represented as polar coordinates at which luminance intensity (units of candela) are measured. The UMTRI report uses the specified FMVSS No. 108 test points to generate an array of 2,220 measurement locations in front of a vehicle. Test points are specified in lateral, longitudinal, and vertical Cartesian coordinates. The origin of the Cartesian coordinate system is at the front of the vehicle on the lateral centerline of the vehicle at the height above the road of the optical center of the headlamps. The test measurements made were illuminance (units of lux).

The report concluded that if implemented, this new approach would add consideration of headlamp mounting height and on-vehicle headlamp aim angle, which are not currently in FMVSS No. 108. Different mounting heights would result in different lateral and longitudinal measurement locations of test points on the roadway for each tested lamp set in order to adapt the polar coordinates of test points listed in FMVSS No. 108, which can in turn impact performance results. Additionally, because the vertical aim angle of a headlamp is important to its performance, by defining photometric limits in vehicle-oriented terms, and measuring photometry with the lamp installed on the vehicle this could result in only a certain range of headlamp aim angles being able to meet the requirements. Currently, when testing headlamps individually in a lab the headlamps are aimed to appropriate aim angle as listed in S10.18 of FMVSS No. 108. The report noted that such a change could imply that, in order to comply, the headlamps would have to be properly aimed on the vehicle at time of sale.

To avoid having to make the large number of photometric measurements required for 2,220 test points, Flanagan and Sullivan (2011) suggested:

However, in practice it would probably be more efficient to make the actual light measurements in a more traditional way, by measuring individual lamps (or “contributors”) on a goniometer and combining the outputs of those lamps in software. Lamp output would be represented by traditional candela matrices, and the mounting locations and orientations of lamps would be represented by simple parameters that would allow the calculation of illuminance at any point in three-dimensional space around the vehicle. This strategy—which might be referred to as virtual vehicle-based photometry—would avoid the need to construct a large physical facility and would still provide all of the benefits of actual vehicle-based photometry, since using software to combine measurements is straightforward.

It is worth noting that this method of measuring individual lamps on a goniometer would be able to capture more data with an efficient, more accessible test procedure than a full on-vehicle test method.

## **Approach**

Considering the past research that was reviewed, a candidate test procedure for assessing the photometric performance on-vehicle of a vehicle's lower beam headlighting system was developed. The test procedure's general approach was modeled after previous NHTSA work (Mazzae et al., 2019) that sought to evaluate a draft test procedure (Mazzae et al., 2019) for confirming visibility performance of lower beam headlighting on a full production vehicle. The previous work by Flannigan and Sullivan (2011) assessed the feasibility of a performance-based approach to headlamp measurement and provided a method to translate FMVSS No. 108 photometric test points in polar coordinates to road locations in Cartesian coordinates.

To assess the candidate test procedure developed, seven test vehicles of MY 2019 or newer were measured. The test vehicles were longitudinally and laterally aligned to the Cartesian coordinates of the test area designated for this effort. The illuminance from the combined set of headlamps was measured with both headlamps aimed to the vehicle manufacturer's target vertical aim angle specification.

Repeatability testing of the lower beam headlighting system performance on-vehicle test procedure was performed with five full test repetitions for a single test vehicle (the 2022 Toyota Camry). Analysis of the repeatability test data highlighted the sensitivity of measurements made near a lamp's cutoff line. Measurements showed that test points at the nominal vertical aim angle (referred to below as the "horizontal line points") had much higher coefficients of variation than test locations further from the nominal vertical aim angle.

After all on-vehicle headlighting system performance testing was completed, the headlamps were removed from the test vehicles and sent to an ISO accredited photometric test lab to be measured. Each lamp was measured while mounted on its own model-specific, supplier-designed test fixture which is used for current FMVSS No. 108 photometric compliance testing. Headlamps were measured for FMVSS No. 108 lower beam headlamp photometry and ISO-candela scans. The ISO-candela scans were used to extract values that corresponded to the test locations used in the on-vehicle testing. The lab-based results were then compared to the on-vehicle test results.

## Method

This section describes the details of the draft test procedure for measuring lower beam headlighting system performance in illuminating the forward roadway.

### Test Procedure Approach

#### *Measurement Method*

NHTSA's 2019 research report on the development of a test procedure for evaluating lower beam headlamp visibility performance documented an approach to on-vehicle headlighting system illumination measurement using an array of forward roadway points. Several aspects of that testing were adopted for this effort. Like that testing, this effort used illuminance receptor heads to measure illuminance at specified measurement locations. Also, like the published draft lower beam headlighting system visibility confirmation test procedure, different receptor head heights were used to evaluate different aspects of the beam pattern. Test points were located above, at, and below the horizon, as will be described in the next section. Illuminance receptor heads for all test locations were positioned vertically, i.e. with the perpendicular axis going through the center of the receptor head hemisphere parallel to the travel direction of the vehicle. Measurement duration and calculation were also adapted from the draft test procedure. Measurements and ambient readings were recorded over a specific time interval and averaged to give a single value.

Although FMVSS No. 108 measures each vehicle headlamp individually, to evaluate a performance-based approach Flannagan and Sullivan (2011) and this effort measured the illuminance produced by having both headlamps for each vehicle illuminated simultaneously (i.e., the way that headlamps are actually operated on an in-use vehicle).

#### *Measurement Locations*

As previously stated, current lab-based photometric testing, including what is specified in FMVSS No. 108, denotes measurement locations in terms of polar coordinates. These polar coordinates are listed as a vertical and horizontal angle, which are measured from the axis going through the photometric center of the lamp in the direction of light projection and centered at the photometric center of the lamp. For vertical angles, Up (U) is positive and Down (D) is negative. For horizontal angles, Right (R) is positive and Left (L) is negative. An angle of 0° is denoted as H for vertical angles and V for horizontal angles, FMVSS No. 108 specifies for current laboratory photometric testing that headlamps are tested at a distance of at least 18.3 m (60 ft) between the lamp and the photometer.

Like most headlamps on the current U.S market, all headlamps tested in this effort used VOA<sup>1</sup>. Furthermore, all headlamps tested were classified as being of type LB2V.<sup>2</sup> Illuminance measurement locations were determined by translating the specified test points in Table XIX-a

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<sup>1</sup> "VISUAL/OPTICAL AIMING" (VOA)

"Terminology and markings used on headlamps in the USA and Canada which denote that a headlamp is to be aimed by visual or optical methods to an aiming screen or prepared wall." (From SAE J599, 2015).

<sup>2</sup> LB2V per Table II of FMVSS No. 108 refers to the photometry requirements in Table XIX-a of FMVSS No. 108 for a lower beam headlamp using visual optical aim for a two-lamp system.

LB2V of FMVSS No. 108 from lab-based points in polar coordinates to points on the test facility surface. The transformation of polar coordinates to road coordinates was based on Flannagan and Sullivan (2011). As in that report, points are geometrically translated from polar coordinates to Cartesian locations across a level roadway surface, with some values and assumptions needed to determine the exact locations of measurement locations. The roadway setting consisted of a straight road with a standard lane width of 3.6 m (12 ft), as was used by Flannagan and Sullivan.<sup>3</sup> Appropriate illuminance receptor head heights were determined in order to accommodate physical measurements.

Note that the test area 10U to 90U – 90L to 90R of Table XIX-a of FMVSS No. 108 was not used in the current research, due to the objectives of the testing and time and equipment constraints for the testing associated with this effort.

The following assumptions were made to translate the polar coordinates of the FMVSS No. 108 Table XIX-a LB2V test locations into road-based measurement locations:

- For test locations 2° or more above the horizon:
  - Illuminance receptor heads were mounted at a height of 2 m.
    - Note that using a taller height would result in longer test distances. At long test distances, the illuminance values would be too small to measure accurately.
- For test locations above the horizon by less than 2°:
  - Illuminance receptor heads were mounted at a height of 1.1 m.
    - This is based on the glare test point location used in Flannagan and Sullivan which is based on average driver eye height.
  - Additionally, FMVSS No. 108 lower beam headlamp glare control locations scan across a vertical angle between a start and end horizontal angle. For this research, unlike the work done by Flannagan and Sullivan, test subpoints at a few relevant locations were used to judge illuminance levels along a line for these scans:
    - The start point,
    - The intersection with the left or right (as appropriate) edge of a standard highway lane that is 3.6 m wide,
    - The intersection with the center of a left or right (as appropriate) adjacent lane that is 3.6 m wide, and
    - The end point of the scan line.
- For test locations at the horizon (i.e., a vertical polar coordinate of zero):
  - The test point height used for each vehicle was the height of that vehicle's headlamp's optical center, and
  - A longitudinal test distance of 10 m was used.

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<sup>3</sup> NHTSA's draft lower beam headlighting system visibility confirmation test procedure (Mazzae et al., 2019) uses a lane width of 4 m.

- For test locations below the horizon:
  - The illuminance receptor head was placed 0.2 m vertically above the ground surface. The illuminance receptor head location was adjusted such that it was in-line with the polar coordinates specified for that test location.
  - The 0.2 m height differs from the approach outlined in Flannagan and Sullivan which sets measurement locations at the road surface level. This is done to accommodate a physical illuminance receptor head instead of the virtual sensor at road level that was suggested by Flannagan and Sullivan.

To calculate the longitudinal and lateral distances from the vehicle at which illuminance receptor heads would be located, the following calculations were made:

1. The absolute two-dimensional distance was calculated by finding where the vertical polar coordinate intersects the plane of the illuminance receptor head height. This was done using the following formula:

$$d_{abs} = \frac{|h_{sensor} - h_{optical\ center}|}{\tan \theta_{vertical}}$$

Where  $d_{abs}$  is the absolute distance to the location,  $h_{sensor}$  is the height of the illuminance receptor head,  $h_{optical\ center}$  is the height of the lower beam headlamp optical center, and  $\theta_{vertical}$  is the vertical angle of the test point in FMVSS No. 108.

2. The longitudinal distance was calculated using the following formula:

$$d_{long} = d_{abs} * \cos \theta_{horizontal}$$

Where  $d_{long}$  is the longitudinal distance to the location,  $d_{abs}$  is the absolute distance to the location, and  $\theta_{horizontal}$  is the horizontal angle of the test point in FMVSS No. 108.

3. The lateral distance was calculated using the following formula:

$$d_{lat} = d_{abs} * \sin \theta_{horizontal}$$

Where  $d_{lat}$  is the longitudinal distance to the location,  $d_{abs}$  is the absolute distance to the location, and  $\theta_{horizontal}$  is the horizontal angle of the test point in FMVSS No. 108.

The lateral and longitudinal origin, or point (0,0), for calculating each translated test point location was the most forward point of the vehicle body at the lateral center of the vehicle, not including any additional body pieces such as license plate mounts. The lamp height was used as the start of the projection of the polar coordinate on to the roadway.

Table 1 shows the relationship between each on-vehicle measurement point and the corresponding FMVSS No. 108 test locations. Due to geometric constraints where the test line ended before it reached the right lane edge, Subpoint 7b was not measured for all vehicles.

Table 1. FMVSS No. 108 Lower Beam Headlamp Photometric Regulation Test Locations

Test Point	Test Point Location	Test Point/Line	Up or Down Angle (°)	Right or Left Angle (°)	Subpoint	Location Along Line
1	2° or More Above the Horizon	4U - 8L	4	-8		
2		4U - 8R	4	8		
3		2U - 4L	2	-4		
4	Above the Horizon by Less Than 2°	1.5U - 1R to 3R & 1.5U 1R to R	1.5	1	a	Start
				3	b	End (3R)
				variable	c	Right Lane Edge
				variable	d	Right Adjacent Lane Center
5		1U - 1.5L to L	1	-1.5	a	Start
				variable	b	Left Lane Edge
				variable	c	Left Adjacent Lane Center
6		0.5U - 1.5L to L	0.5	-1.5	a	Start
				variable	b	Left Lane Edge
				variable	c	Left Adjacent Lane Center
7		0.5U - 1R to 3R	0.5	1	a	Start
				variable	b	Right Lane Edge (if applicable)
	3			c	End	
8	At the Horizon	H - 4L	0	-4		
9		H - 8L	0	-8		
10	Below the Horizon	0.6D - 1.3R	-0.6	1.3		
11		0.86D - V	-0.86	0		
12		0.86D - 3.5L	-0.86	-3.5		
13		1.5D - 2R	-1.5	2		
14		2D - 9L	-2	-9		
15		2D - 9R	-2	9		
16		2D - 15L	-2	-15		
17		2D - 15R	-2	15		
18		4D - 4R	-4	4		
19		4D - 20L	-4	-20		
20		4D - 20R	-4	20		

A representation of the test locations for a lamp height of 0.62 m is depicted in Figure 1.

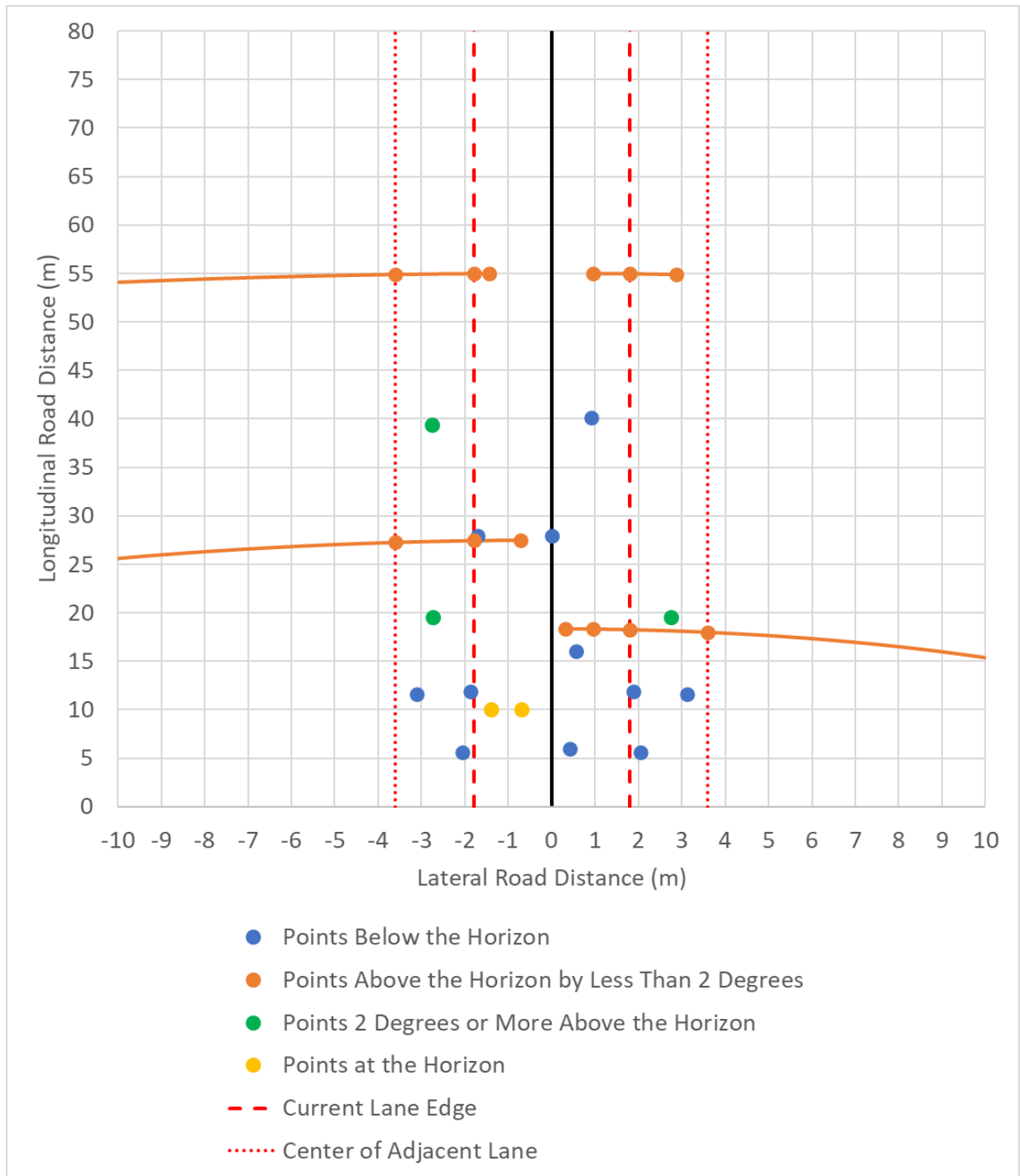


Figure 1. Example Illuminance Measurement Locations and Added Glare Value Locations

Illuminance receptor heads were mounted on tripods to position them at the required height vertically above the test surface. The receptor heads were positioned such that the perpendicular axis going through the center of the receptor head hemisphere was parallel to the test vehicle travel direction. The test surface used was flat, level asphalt with dimensions that exceeded 80 m

long by 15 m wide. To accommodate such a large area, testing was performed outside on the Vehicle Dynamics Area at Transportation Research Center Inc. All measurement locations were marked on the test surface to permit repeatable placement of the illuminance receptor heads. Figure 2 shows an example of the test setup including vehicle positioning and illuminance receptor head array locations on the forward roadway surface.



*Figure 2. Illuminance Receptor Head Array and Test Vehicle Setup*

### **Headlamp Vertical Aim Angle**

Headlamp vertical aiming was performed based on the procedures contained in the November 2015 version of SAE J599, *Lighting inspection code* (SAE International, 2015).

To perform headlamp vertical aiming, the term “cutoff line” needs to be defined. In addition to use with regard to headlamp vertical aiming, the concept of “cutoff line” will be used when examining test results.

The “cutoff line” of a lower beam headlamp is the light/dark boundary at the top of the light pattern produced by a lower beam headlamp. As specified in SAE J599, the concept of “gradient” of the illuminance produced by the headlamp is used to determine the location of the cutoff line. Since the vehicles tested during this research all had VOR (Visual/Optical – Right)<sup>4</sup>

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<sup>4</sup> “VOR (Visual/Optical – Right)”

“Lens marking indicating a low beam lamp that is to be aimed by using the cutoff gradient feature to the top, right side of the beam.” (From SAE J599, 2015).

headlamps (see Table 5), Figure 3, Aim inspection limits for a VOR low beam per SAE J599, shows how the cutoff line is determined and where the cutoff line is to be located for a properly aimed headlamp.

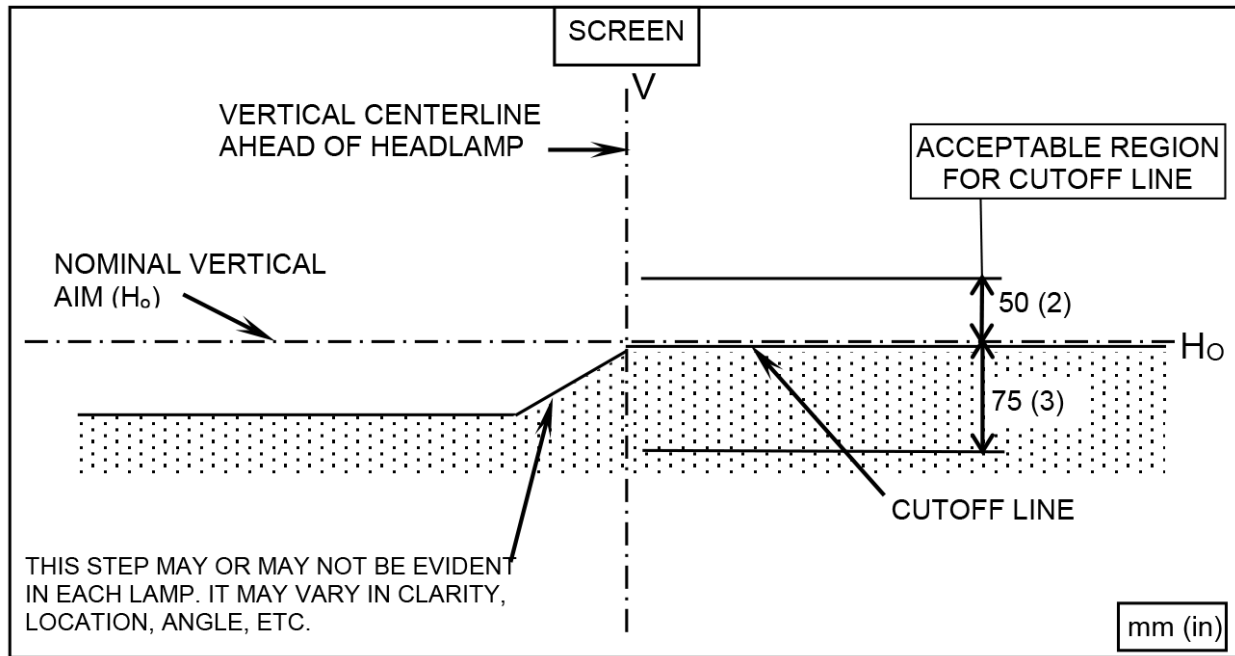


Figure 3. Aim Inspection Limits for a VOR Low Beam From SAE J599

While Figure 3, as shown in SAE J599, permits a range of locations for a properly aimed headlamp, in the work that follows, a vertical aim angle of  $0.00^\circ$  corresponds to having the cutoff line located at the manufacturer's vertical aim angle specification. As vertical aim angle is increased, the cutoff line moves up. Similarly, as vertical aim angle is decreased, the cutoff line moves down.

Headlamps were aimed vertically for each set of measurements using an imaging photometer. The photometer collects images of the headlamp beam pattern projected on a screen that is 7.6 m away from the front-most point of the vehicle. The image is captured and then analyzed in software that works with the photometer. In the software, the gradient was measured vertically on a line  $2^\circ$  to the right of the vertical line going through the optical center of the lower beam headlamp. The gradient was measured from  $1.5^\circ$  up to  $1.5^\circ$  down at a pitch of  $0.02^\circ$ . The gradient was then calculated for each point by the formula:

$$G_a = \log(x_a) - \log(x_{a+0.1^\circ})$$

where  $G_a$  is the gradient at point "a",  $x_a$  is the luminous intensity at point "a", and  $x_{a+0.1^\circ}$  is the luminous intensity of the point  $0.1^\circ$  above "a". The maximum gradient and corresponding location are found, and the headlamp adjusted, such that the maximum gradient is at the required aim location.

## Test Equipment

### ***Illuminance Measurement Equipment***

A Konica Minolta<sup>5</sup> T-10A illuminance meter was used to measure the amount of light emitted by a vehicle's lower beam headlamps. The T-10A is a multi-function digital illuminance meter with a detachable receptor head. The T-10A has an operating temperature range of 14 to 104° Fahrenheit (-10 to 40 degrees Celsius) and specified operating conditions of 85 percent or less relative humidity (at 35°C or colder) with no condensation. Appendix A contains the complete specifications for the Konica Minolta T-10A illuminance meter.

The illuminance meter (Figure 4) has the capability to record both single-point (using analog output) and multi-point (using digital output) measurements. The meter can perform single-point measurements instantaneously or record continuous single-point measurements using its analog output. Multi-point measurement requires that the meter be powered using an approved AC adapter and that two or more receptor heads be connected to the meter using adapters (T-A21) and commercially available 10Base-T network cables (category 5 straight cable).



*Figure 4. Konica Minolta T-10A Illuminance Meter [10]*

For this effort, multi-point measurement was performed in which the meter was fitted with a T-A20 main body adaptor, and each receptor head was fitted with a T-A21 receptor head adapter. Using the T-A21 adaptors, category 5 cables were connected between each receptor head in series and to the meter. Per the meter's instruction manual, the recommended AC adapter was used to power the meter during multi-point measurement. The AC adapter was connected to a power inverter and then to a Schumacher<sup>6</sup> PSJ-3612 Jump Starter and Portable Power Unit that provided power. The power inverter was powered through the vehicle's cigarette lighter. Software developed by NHTSA to run on a Windows-based tablet and interface with the

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<sup>5</sup> Konica Minolta, Inc., Marunouchi, Chiyoda, Tokyo.

<sup>6</sup> Schumacher Electric, Dallas/Fort Worth, TX.

illuminance meter was used to record data. Figure 5 is an image showing how the components were used in the multi-point meter configuration. Illuminance measurements were captured over a specified duration (e.g., 30 seconds) at a rate of 1 Hz.



*Figure 5. Illuminance Meter and Additional Receptor Heads Used for Multi-Point Measurement [11]*

Model and serial number information for the meter and receptor heads as components used in the testing are provided in Table 2. The table also shows which specific receptor heads were used in each measurement location.

Table 2. Model and Test Location Information for Illuminance Meter Components

Component Label	Serial Number	FMVSS Test Location	Location Label	Height
Konica-Minolta T-10A	20020976	N/A	N/A	N/A
Receptor Head 00 (RH00)	30022422	4U - 8L	1	2 m
Receptor Head 01 (RH01)	30022436	4U - 8R	2	2 m
Receptor Head 02 (RH02)	30022472	2U - 4L	3	2 m
Receptor Head 03 (RH03)	30022474	1.5U - 1R to 3R/R	4a	1.1 m
Receptor Head 04 (RH04)	30022418		4b	1.1 m
Receptor Head 05 (RH05)	30022473		4c	1.1 m
Receptor Head 06 (RH06)	30022435		4d	1.1 m
Receptor Head 07 (RH07)	30022437	1U - 1.5L to L	5a	1.1 m
Receptor Head 08 (RH08)	30022421		5b	1.1 m
Receptor Head 09 (RH09)	30022420		5c	1.1 m
Receptor Head 10 (RH10)	30022432	0.5U - 1.5L to L	6a	1.1 m
Receptor Head 11 (RH11)	30022419		6b	1.1 m
Receptor Head 12 (RH12)	30022434		6c	1.1 m
Receptor Head 13 (RH13)	30015510	0.5U - 1R to 3R	7a	1.1 m
Receptor Head 14 (RH14)	30011924		7b	1.1 m
Receptor Head 15 (RH15)	30011928		7c	1.1 m
Receptor Head 16 (RH16)	30012155	H - 4L	8	Headlamp Mounting Height
Receptor Head 17 (RH17)	30015512	H - 8L	9	Headlamp Mounting Height
Receptor Head 18 (RH18)	30012026	0.6D - 1.3R	10	0.2 m
Receptor Head 19 (RH19)	30015294	0.86D - V	11	0.2 m
Receptor Head 20 (RH20)	30012154	0.86D - 3.5L	12	0.2 m
Receptor Head 21 (RH21)	30015768	1.5D - 2R	13	0.2 m
Receptor Head 22 (RH22)	30015296	2D - 9L	14	0.2 m
Receptor Head 23 (RH23)	30013094	2D - 9R	15	0.2 m
Receptor Head 24 (RH24)	30011417	2D - 15L	16	0.2 m
Receptor Head 25 (RH25)	30011925	2D - 15R	17	0.2 m
Receptor Head 26 (RH26)	30022573	4D - 4R	18	0.2 m
Receptor Head 27 (RH27)	30022576	4D - 20L	19	0.2 m
Receptor Head 28 (RH28)	30022574	4D - 20R	20	0.2 m

## ***Test Vehicle Positioning Aids***

Steps were taken to accurately position test vehicles in the center of the designated lane on the test surface. A centerline was marked on the road surface that all vehicles were aligned to. The line started at the origin of the cartesian coordinate system for measuring and was parallel to the longitudinal direction for point marking. Plumb bobs were attached to the center of the front and rear of the vehicle under test. The car was then positioned such that the front plumb bob was at the start of the centerline, and the rear plumb bob was also on the centerline.

## ***Headlamp Aim Measurement Equipment***

To aim the headlamps to the vehicle manufacturer's vertical aim angle specification, an imaging photometer was used to measure the cutoff line location. The photometer (shown in Figure 6) used was a Radiant Vision Systems<sup>7</sup> ProMetric Y Imaging Photometer. This model has a 16 mega-pixel resolution and uses a CMOS sensor. It is equipped with a lens with an electronic focus and aperture to ensure the correct field of view for measurement. The photometer was connected to a computer for analysis via a CAT5 Ethernet cable and was powered via its recommended AC adapter. The corresponding ProMetric software was used to analyze measurements and determine the aim of the headlamps, in support of any needed adjustments.



*Figure 6. Radiant Vision Systems ProMetric Y Imaging Photometer*

The imaging photometer takes an illuminance measurement from a surface. The primary surface used for this measurement was a large (9.5 ft wide by 4.75 ft tall) matte finish floor-rising projection screen, as shown in Figure 7. The large screen had sufficient surface area to be able to capture both headlamps' gradient areas at once. The large screen was deployed by pulling it up from its casing on the ground for taking measurements and then lowered and stowed in its casing after each aim adjustment was complete. The large screen would bow in conditions of significant wind speed. Therefore, two smaller screens (see Figure 8) were used in windy conditions, one for each headlamp, large enough to capture a single headlamp's gradient measurement. These smaller screens measured 2 ft wide by 3 ft tall. The smaller screens were mounted on carts with locking wheels and not as susceptible to the wind. Markers were placed on the ground to ensure repeatable screen placement on the test surface.

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<sup>7</sup> Radiant Vision Systems, Redmond, WA.



*Figure 7. Aim Screen – Large Screen*



*Figure 8. Aim Screen – Small Screen*

### ***Light-Blocking Equipment***

Some aspects of the test procedure required the blocking of light from one or both headlamps. In order to aim each headlamp individually, the beam pattern from the other headlamp would need to be absent. Also, when ambient illumination readings were taken for a measurement, the beam pattern of both headlamps needed to be absent from the test area. Removing the light from one or both lamps could not be accomplished by turning off the vehicle or headlamps since it was important to maintain a consistent temperature in the headlamps. Therefore, a light block strategy was used that allowed the lamps to remain powered while keeping their light from being cast in the area forward of the test vehicle. Lighting blocking was accomplished using a light-blocking black curtains hung from a frame that were placed in front of the test vehicles. The frame extended such that each curtain could be moved to block light from one lamp, both lamps, or neither lamp. Bungee cords were used to hold the curtains in place while in use or being placed off to the side.

### **Test Surface**

Testing was conducted on a flat, level asphalt test surface with dimensions that exceeded 80 m long by 15 m wide. For the effort documented in this report, testing was conducted on the Vehicle Dynamics Area facility of the Transportation Research Center proving ground.

### **Test Vehicle Preparation**

Each vehicle was prepared for testing by filling the fuel tank and ensuring the test vehicle's tires were set to the vehicle manufacturers recommended cold inflation pressures. The vehicle's hood, trunk, and all doors were closed, and the steering wheel was adjusted to the position where the longitudinal centerlines of all vehicle tires were parallel to the longitudinal centerline of the vehicle. Vehicle battery voltage level was confirmed to be within the nominal operating range (e.g., +11 to +16 V DC). The vehicle was loaded to simulate the weight of a driver. The weight of the driver was represented by weights placed in the driver's designated seating area, consisting of 45 kg (100 lb) resting on the seat pan and 23 kg (50 lb) resting on the vehicle floorboard. The test vehicle and headlamps were powered on for at least 30 minutes before testing began.

### **Test Conditions**

The ambient illumination conditions were required be less than 0.200 lux at each of the specified measurement locations with the test vehicle's headlamps powered off measured from the receptor heads in their test position.

Ambient temperature, humidity, and wind speed information was obtained from the test facility's official conditions measurement data. The test procedure called for ambient temperature to be within the operating range of the measurement equipment but also between 5°C and 40°C (41°F and 104°F) and wind speed less than 35 kph (21.75 mph). Tests were not performed during periods of inclement weather including, but not limited to, rain, snow, hail, fog, smoke, and/or ash.

## Test Procedures – On-Vehicle

### **Headlamp Aiming**

For test results discussed in this report, the headlamps were aimed to their manufacturer’s target aim specification. The lower beam headlamp pattern was then measured at the test locations specified in Table 1. The imaging photometer was placed just forward of the center of the vehicle’s front bumper, such that the camera could capture both beam patterns without the need to set up the camera for each headlamp’s aim adjustment. To accommodate the static position of the imaging photometer, the gradient locations were calculated with respect to the center of the vehicle. The corresponding gradient locations for each centered imaging photometer were calculated using the following formulas:

$$\theta_D = \tan^{-1} \frac{(d * \tan \theta_{VOA}) - w/2}{d}$$
$$\theta_P = \tan^{-1} \frac{(d * \tan \theta_{VOA}) + w/2}{d}$$

Where  $\theta_D$  is the measurement angle to the driver-side lower beam headlamp optical center,  $\theta_P$  is the measurement angle to the passenger-side lower beam headlamp optical center,  $d$  is the distance to the screen,  $\theta_{VOA}$  is the gradient measurement angle designated in FMVSS No. 108 for the corresponding headlamp, and  $w$  is lateral distance between the vehicle’s two lower beam headlamp optical centers.

The following specifies the procedure for ensuring that the headlamps are properly aimed:

1. Place the headlamp-aiming screen 7.6 m (25 ft) in front of the vehicle and adjust the screen height to match the headlamp mounting height.
2. Place the imaging photometer in between the vehicle headlamps at the headlamp mounting height.
3. Record an image of the aim screen and calculate the gradient at 2° right of the horizontal lamp location from +1.5° to -1.5° vertically at a 0.02° pitch.
4. Adjust the headlamp aim as needed.
5. Repeat steps 3 and 4 as necessary until the headlamp aim is within +/-0.02° of the required aim.

### **Ambient Illuminance Correction**

Ambient illuminance values obtained at the specified measurement locations were subtracted from the corresponding average headlamp illuminance value for each measurement point to obtain a value for illuminance attributable only to the test vehicle’s headlamps.

### **Test Repeatability Approach**

In order to analyze the repeatability of the test procedure, a single vehicle (a 2022 Toyota Camry) was tested five separate times, each time on a different night. By performing repetitions across nights, this created the need for the vehicle and equipment to be setup new each time.

Measured illuminance data for each test repetition were compared to assess how repeatable the test procedure was for producing the same values across nights.

### **Test Procedures – Lab**

To assess the accuracy of the on-vehicle test procedure, the same headlamps and parking lamps from each test vehicle were removed from the test vehicle and sent to a certified photometric test lab for measurement. Parking lamps were measured in the lab testing for comparison with the on-vehicle testing, since the parking lamps cannot be turned off on-vehicle when low beams are activated. NHTSA and TRC collaborated with the vehicle and lamp manufacturers to acquire the appropriate headlamp-specific test fixtures needed for the laboratory measurements.

Laboratory testing was conducted by Sapphire Technical Solutions using its AP-60HD goniometer system.<sup>8</sup> A goniometer system is the standard measurement system for automotive lighting. It functions by placing a lamp such that its optical center is centered and directly facing the photometer that is a fixed distance away. The system can rotate horizontally and vertically about a lamp's optical center to measure at any desired angle. The following figure shows a headlamp mounted onto a goniometer system.



*Figure 9. AP-60 Goniophotometer*

Each headlamp was tested individually. Results from each set of lamps were combined to obtain a single value for the vehicle.

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<sup>8</sup> Sapphire Technical Solutions, Pineville, NC . The photo is from the company PDF at [https://static1.squarespace.com/static/5c922de77eb88c0228339815/t/5d386b0f93f67a0001590c5a/1563978511697/AP\\_60.pdf](https://static1.squarespace.com/static/5c922de77eb88c0228339815/t/5d386b0f93f67a0001590c5a/1563978511697/AP_60.pdf).

This testing measured photometric intensity values, in candela. Using the distance from the forwardmost point on the centerline of each test vehicle to each test point or subpoint, the candela values were converted into illuminance values, measured in lux.

The following table lists the tests that were performed in the lab.

*Table 3. Lab Tests Performed*

<b>Lamps Tested</b>	<b>Function Tested</b>	<b>Test Performed</b>	<b>Test Details</b>
Headlamps and Parking Lamps from All Seven Test Vehicles	Lower beam	FMVSS No. 108 lower beam photometry	Table XIX-a lower beam #2V (LB2V)
	Front parking	ISO-candela scan	Area bounded by 5U/D and 35R/L at a 0.1° increment in both directions

Any lamp functions that use LEDs were turned on 30 minutes before testing to ensure stability of the light output. The input voltage to the tested lamps was supplied by the goniometer system. The specific design voltage for each lamp was supplied.

The lab tested data was confirmed by the OEMs. The driver’s side lower beam headlamp ISO-candela Scan results were sent to the OEMs to confirm that the beam pattern looked as intended. This confirmed correct headlamp mounting to the test fixture by the test lab.

## Vehicles Tested

Seven recent MY vehicles were examined in this testing. The vehicle model information is summarized in Table 4. The test vehicles' headlighting system information is summarized in Table 5. The height of each vehicle's lower beam headlamps was determined using the optical axis marking on the headlamp lens (typically a mark on the lens in front of the light source).

*Table 4. Test Vehicle Make, Model, and Trim Level Information*

Model Year	Make	Model	Trim Level	VIN	Mileage
2022	Chevrolet	Equinox	Premier AWD	2GNAXXEV4N6	80
2023	Ford	F-150	4x4 Super Crew	1FTFW1ED1PF	158
2019	Ford	Fusion	SE Hybrid	3FA6P0RU2JR	1,959
2022	Hyundai	Tucson	Limited	5NMJECAE0NH	32
2022	Subaru	Outback	Touring	4S4BTAPC3N3	889
2022	Tesla	Model 3	(NA)	5YJ3E1EB9NF	1,107
2022	Toyota	Camry	SE	4T1G11AKXNU	155

*Table 5. Test Vehicle Headlamp Information*

Model Year	Make	Model	VOA Type	SAE J599 Aim, Height Offset	Lower Beam Optic Type	Lower Beam Headlamp		Vehicle Manufacturer Aim Specification
						Height (to nearest cm)	Width (to nearest cm)	
2022	Chevrolet	Equinox	VOR	No Offset	LED Projector	84	147	0° +0.38° to -0.57° (SAE J599)
2023	Ford	F-150	VOR	No Offset	LED Projector	88	154	0° +0.29° to 0.29°
2019	Ford	Fusion	VOR	No Offset	Halogen Projector	72	127	29" +/- 3" at 25' (0° +/- 0.57°)
2022	Hyundai	Tucson	VOR	No Offset	LED Projector	66	145	0° +0.11° to -0°
2022	Subaru	Outback	VOR	No Offset	LED Projector	81	123	Confidential Business Information
2022	Tesla	Model 3	VOR	No Offset	LED Projector	70	150	0° +/- 0.2°
2022	Toyota	Camry	VOR	No Offset	LED Projector	72	146	0° +0.38° to -0.57° (SAE J599)

The Vehicle Manufacturer Aim Specification for the Subaru Outback is listed as Confidential Business Information in Table 5. It was known to the experimenters for testing but is not listed in this report.

All headlamps except the Tesla lamps used a typical mechanical bolt for vertical aiming, which was external to the headlamps. The Tesla headlamps used a LIN interface, a network protocol used for communication within a vehicle, that was used for both activation of lighting functions

and vertical aim adjustment. Due to this, there was no external aim bolt and the aim mechanisms were internal to the headlamps. The vertical and horizontal aim also defaulted to a minimum value on activation of the vehicle. Initially the test lab's best judgement was used to determine where the horizontal aim should be, but when asked to confirm, the headlamp supplier was able to accurately indicate where the lamp horizontal aim should be. With this knowledge, the ISO-candela scan data was shifted by the amount of error in the aim and the data was extracted at the correct aim.

The following are images of the front ends of each vehicle tested.

### **Test Vehicle Photos**

A color photograph of the 2022 Chevrolet Equinox Limited is presented in Figure 10.



*Figure 10. 2022 Chevrolet Equinox Limited - Front*

A color photograph of the 2022 Ford F-150 4x4 is presented in Figure 11.



*Figure 11. 2022 Ford F-150 4x4 - Front*

A color photograph of the 2019 Ford Fusion Hybrid is presented in Figure 12.



*Figure 12. 2019 Ford Fusion Hybrid - Front*

A color photograph of the 2022 Hyundai Tucson Limited is presented in Figure 13.



*Figure 13. 2022 Hyundai Tucson Limited - Front*

A color photograph of the 2022 Subaru Outback Touring is presented in Figure 14.



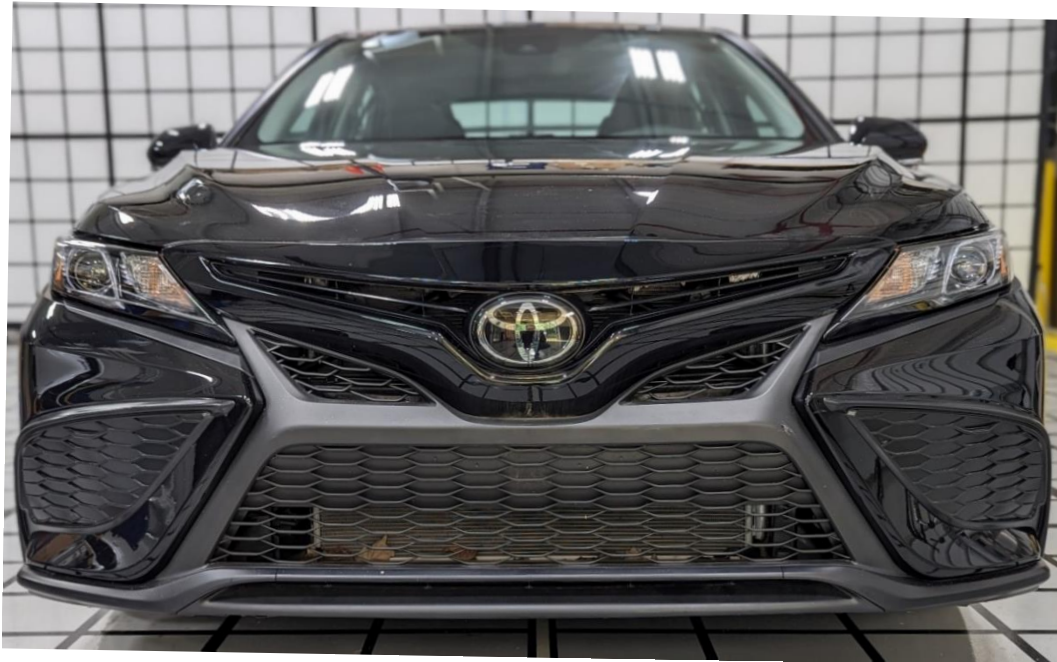
*Figure 14. 2022 Subaru Outback Touring - Front*

A color photograph of the 2022 Tesla Model 3 is presented in Figure 15.



*Figure 15. 2022 Tesla Model 3 - Front*

A color photograph of the 2022 Toyota Camry SE is presented in Figure 16.



*Figure 16. 2022 Toyota Camry SE - Front*

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## **Results for On-Vehicle Testing**

### **Translation of FMVSS No. 108 photometric test points in polar coordinates to roadway locations in Cartesian coordinates**

As described above, FMVSS photometric test points were translated from polar coordinates to roadway locations in Cartesian coordinates. Tables 6 and 7 summarize the forward (measured from front-most point on the centerline of the vehicle), lateral (positive values are to the right of the vehicle centerline, negative values to the left), and vertical (distance above the VDA's surface) coordinates (in m) for each of the FMVSS No. 108 test point and subpoints for each of the vehicles tested during this research. Table 6 encompasses all test locations above the horizon, i.e. with a positive vertical angle, and Table 7 encompasses all test locations or above the horizon, i.e. with a vertical angle that is zero or negative.

Table 6. Test Point and Subpoint Coordinates for Tested Vehicles - Test Locations Above the Horizontal

	Coordinate	1	2	3	4a	4b	4c	4d	5a	5b	5c	6a	6b	6c	7a	7b	7c
<b>2022 Chevrolet Equinox</b>	<b>Forward</b>	16.50	16.50	33.28	10.12	10.11	9.96	9.46	15.18	15.07	14.75	30.35	30.31	30.15	30.36		30.32
	<b>Lateral</b>	-2.32	2.32	-2.33	0.18	0.53	1.80	3.60	-0.40	-1.80	-3.60	-0.79	-1.80	-3.60	0.53		1.59
	<b>Vertical</b>	2.00	2.00	2.00	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	
<b>2023 Ford F-150</b>	<b>Forward</b>	15.96	15.96	32.09	8.50	8.49	8.31	7.69	12.70	12.57	12.18	25.30	25.25	25.05	25.31		25.27
	<b>Lateral</b>	-2.23	2.23	-2.24	0.15	0.44	1.80	3.60	-0.33	-1.80	-3.60	-0.66	-1.80	-3.60	0.44		1.32
	<b>Vertical</b>	2.00	2.00	2.00	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	
<b>2019 Ford Fusion</b>	<b>Forward</b>	18.17	18.17	36.55	14.46	14.44	14.35	14.46	21.63	21.57	21.34	43.17	43.15	43.03	43.18	43.15	43.13
	<b>Lateral</b>	-2.54	2.54	-2.55	0.25	0.75	1.80	0.00	-0.56	-1.80	-3.60	-1.13	-1.80	-3.60	0.75	1.80	2.25
	<b>Vertical</b>	2.00	2.00	2.00	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
<b>2022 Hyundai Tucson</b>	<b>Forward</b>	19.02	19.02	38.27	16.76	16.74	16.66	16.37	25.09	25.03	24.83	50.08	50.06	49.97	50.09	50.06	50.03
	<b>Lateral</b>	-2.66	2.66	-2.67	0.29	0.87	1.80	3.60	-0.65	-1.80	-3.60	-1.31	-1.80	-3.60	0.87	1.80	2.62
	<b>Vertical</b>	2.00	2.00	2.00	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
<b>2022 Subaru Outback</b>	<b>Forward</b>	16.93	16.93	34.06	11.12	11.11	10.98	10.52	16.64	16.54	16.24	33.17	33.14	32.99	33.18		33.14
	<b>Lateral</b>	-2.37	2.37	-2.37	0.19	0.58	1.80	3.60	-0.43	-1.80	-3.60	-0.87	-1.80	-3.60	0.58		1.73
	<b>Vertical</b>	2.00	2.00	2.00	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	
<b>2022 Tesla Model 3</b>	<b>Forward</b>	18.46	18.46	37.14	15.25	15.23	15.14	14.81	22.82	22.75	22.54	45.54	45.52	45.41	45.55	45.52	45.49
	<b>Lateral</b>	-2.58	2.58	-2.59	0.26	0.79	1.80	3.60	-0.59	-1.80	-3.60	-1.19	-1.80	-3.60	0.79	1.80	2.38
	<b>Vertical</b>	2.00	2.00	2.00	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
<b>2022 Toyota Camry</b>	<b>Forward</b>	18.26	18.26	36.74	14.70	14.69	14.59	14.25	22.00	21.94	21.71	43.91	43.89	43.78	43.92	43.89	43.86
	<b>Lateral</b>	-2.55	2.55	-2.56	0.25	0.76	1.80	3.60	-0.57	-1.80	-3.60	-1.15	-1.80	-3.60	0.76	1.80	2.29
	<b>Vertical</b>	2.00	2.00	2.00	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10

Table 7. Test Point Coordinates for Tested Vehicles - Test Locations at or Below the Horizontal

	Coordinate	8	9	10	11	12	13	14	15	16	17	18	19	20
<b>2022 Chevrolet Equinox</b>	<b>Forward</b>	10.00	10.00	60.62	42.30	42.23	24.24	17.96	17.96	17.57	17.57	9.06	8.53	8.53
	<b>Lateral</b>	-0.70	-1.41	1.38	0.00	-2.58	0.85	-2.84	2.84	-4.71	4.71	0.63	-3.11	3.11
	<b>Vertical</b>	Variable	Variable	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
<b>2023 Ford F-150</b>	<b>Forward</b>	10.00	10.00	64.92	45.30	45.22	25.95	19.23	19.23	18.81	18.81	9.70	9.14	9.14
	<b>Lateral</b>	-0.71	-1.42	1.47	0.00	-2.77	0.91	-3.05	3.05	-5.04	5.04	0.68	-3.33	3.33
	<b>Vertical</b>	Variable	Variable	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
<b>2019 Ford Fusion</b>	<b>Forward</b>	10.00	10.00	50.02	34.91	34.84	20.00	14.82	14.82	14.49	14.49	7.48	7.04	7.04
	<b>Lateral</b>	-0.71	-1.42	1.14	0.00	-2.13	0.70	-2.35	2.35	-3.88	3.88	0.52	-2.56	2.56
	<b>Vertical</b>	Variable	Variable	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
<b>2022 Hyundai Tucson</b>	<b>Forward</b>	10.00	10.00	44.27	30.89	30.83	17.70	13.12	13.12	12.83	12.83	6.62	6.23	6.23
	<b>Lateral</b>	-0.71	-1.42	1.00	0.00	-1.89	0.62	-2.08	2.08	-3.44	3.44	0.46	-2.27	2.27
	<b>Vertical</b>	Variable	Variable	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
<b>2022 Subaru Outback</b>	<b>Forward</b>	10.00	10.00	58.36	40.72	40.65	23.33	17.29	17.29	16.91	16.91	8.72	8.21	8.21
	<b>Lateral</b>	-0.71	-1.42	1.32	0.00	-2.49	0.81	-2.74	2.74	-4.53	4.53	0.61	-2.99	2.99
	<b>Vertical</b>	Variable	Variable	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
<b>2022 Tesla Model 3</b>	<b>Forward</b>	10.00	10.00	48.05	33.53	33.47	19.21	14.24	14.24	13.92	13.92	7.18	6.76	6.76
	<b>Lateral</b>	-0.71	-1.42	1.09	0.00	-2.05	0.67	-2.25	2.25	-3.73	3.73	0.50	-2.46	2.46
	<b>Vertical</b>	Variable	Variable	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
<b>2022 Toyota Camry</b>	<b>Forward</b>	10.10	10.10	49.41	34.48	34.41	19.75	14.64	14.64	14.32	14.32	7.38	6.95	6.95
	<b>Lateral</b>	-0.71	-1.42	1.12	0.00	-2.10	0.69	-2.32	2.32	-3.84	3.84	0.52	-2.53	2.53
	<b>Vertical</b>	Variable	Variable	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

## **On-Vehicle Measured Values**

This section shows the results of the on-vehicle testing. Tables 8 and 9 show the illuminance measured at the manufacturers' target aim specification for each vehicle tested. To more easily view the data, test locations have been split between those above the horizontal (Table 8), and those at or below the horizontal (Table 9). For the 2022 Toyota Camry, the values shown are the average value from the five test repetitions that were performed for this vehicle.

*Table 8. On-Vehicle Illuminance Data at OEM Vertical Aim Angle Specification- Test Locations Above the Horizontal*

Test Vehicle	Test Point or Subpoint Illuminance Values in lux															
	1	2	3	4a	4b	4c	4d	5a	5b	5c	6a	6b	6c	7a	7b	7c
<b>2022 Chevrolet Equinox</b>	1.8	1.9	1.1	5.8	6.7	5.8	9.9	2.6	2.1	2.7	1.3	1.0	0.8	1.1		1.2
<b>2023 Ford F-150</b>	3.8	3.8	1.3	15.5	17.9	17.4	9.8	10.4	6.2	3.7	5.9	3.4	1.8	5.0		5.8
<b>2019 Ford Fusion</b>	1.4	0.8	0.7	3.5	2.8	2.5	8.9	2.5	2.1	2.3	1.1	0.7	0.8	0.6	0.5	0.4
<b>2022 Hyundai Tucson</b>	1.8	1.2	0.8	4.1	4.0	2.8	1.1	2.4	2.1	1.8	0.8	0.8	0.6	0.8	0.8	0.7
<b>2022 Subaru Outback</b>	1.7	1.3	1.0	8.5	7.4	4.5	1.6	4.6	3.7	2.2	2.6	1.9	1.1	2.8		1.3
<b>2022 Tesla Model 3</b>	1.4	1.3	1.0	4.8	4.4	3.4	4.2	3.0	2.5	1.8	1.2	0.9	0.6	0.9	1.1	1.1
<b>2022 Toyota Camry (average)</b>	1.3	1.1	0.8	4.7	4.3	3.2	1.7	2.7	2.1	1.6	1.4	1.3	0.7	1.5	1.5	1.4

*Table 9. On-Vehicle Illuminance Data at OEM Vertical Aim Angle Specification - Test Locations at or Below the Horizontal*

Test Vehicle	Test Point Illuminance Values in lux												
	8	9	10	11	12	13	14	15	16	17	18	19	20
<b>2022 Chevrolet Equinox</b>	85.0	33.0	14.4	31.2	29.0	66.8	87.7	84.8	68.3	49.4	270.3	143.3	101.9
<b>2023 Ford F-150</b>	205.4	16.3	18.5	26.3	28.9	84.7	75.0	47.7	37.3	24.6	124.9	59.8	48.2
<b>2019 Ford Fusion</b>	64.6	42.4	6.7	24.0	25.9	53.2	42.9	19.9	13.5	9.3	147.8	23.4	17.3
<b>2022 Hyundai Tucson</b>	99.2	45.0	32.8	79.5	55.9	210.0	227.2	190.9	135.9	97.5	447.6	186.4	156.4
<b>2022 Subaru Outback</b>	378.3	36.2	23.2	58.1	41.6	69.4	71.9	54.4	48.2	31.2	162.4	86.2	51.6
<b>2022 Tesla Model 3</b>	98.2	45.3	27.2	81.3	74.8	179.8	91.4	116.1	126.5	69.8	257.2	167.6	96.8
<b>2022 Toyota Camry (average)</b>	111.0	22.2	31.7	74.9	47.4	136.1	112.2	74.9	60.9	40.7	233.5	120.1	85.2

## Lab Testing Results

Test vehicles' headlamps and parking lamps were removed and sent to a photometric test lab for measurement. NHTSA and TRC collaborated with the vehicle and lamp manufacturers to acquire the appropriate test fixtures needed for the laboratory measurements. Laboratory testing was conducted by Sapphire Technical Solutions using a AP-60 goniometer system. For each set of headlamps and parking lamp, each lamp was tested individually. Results from each set of lamps were combined to a single value for the vehicle.

This testing measured photometric intensity values, in candela. Using the distance from the forwardmost point on the centerline of each test vehicle to each test point or subpoint, the candela values were converted into illuminance values, measured in lux.

## Laboratory Testing Calculations

FMVSS No. 108 lower beam photometry points were extracted from the ISO-candela scan data by finding the vertical and horizontal angles. Required angle values were rounded to the nearest  $0.1^\circ$  as this was the resolution for the ISO-candela measurements. The vertical and horizontal angles were calculated by the following formulas:

$$\theta_{UD} = \left( 90 - \tan^{-1} \frac{\sqrt{d_{long}^2 + (d_{lat} - w)^2}}{h_{RH} - h_{function}} \right)$$

$$\theta_{RL} = \tan^{-1} \frac{d_{lat-w}}{d_{long}}$$

Where  $\theta_{UD}$  is the vertical angle,  $\theta_{RL}$  is horizontal angle,  $d_{long}$  is the longitudinal distance of the test location,  $d_{lat}$  is the lateral distance of the test location,  $w$  is the lateral location of the lamp,  $h_{RH}$  is the height of the receptor head, and  $h_{function}$  is the height of the optical center of the function.

After the intensity value was extracted from the ISO-candel data, the intensity value was calculated as an illuminance value by the following formula:

$$E_{V} = \frac{I_V}{d_{long}^2 + (d_{lat-w})^2 + (h_{RH} - h_{function})^2}$$

Where  $E_V$  is the illuminance at the test location and  $I_V$  is the luminance intensity from the ISO-candela measurement.

The illuminance contribution from the driver side and passenger side lower beam headlamps and front park functions were then added together to compare with the on-vehicle measurements.

## **Laboratory Testing Data**

This section shows the results of the lab testing without any comparison to on-vehicle measurements. Tables 10 and 11 show the illuminance measured at the manufacturers' target aim spec for each vehicle tested. To view the data more easily, test locations have been split between those above the horizontal (Table 10), and those at or below the horizontal (Table 11).

*Table 10. Laboratory Illuminance Data at OEM Vertical Aim Angle Target - Test Locations Above the Horizontal*

Test Vehicle	Test Point or Subpoint Illuminance Values in lux															
	1	2	3	4a	4b	4c	4d	5a	5b	5c	6a	6b	6c	7a	7b	7c
<b>2022 Chevrolet Equinox</b>	1.4	1.3	0.6	5.0	5.4	4.2	9.5	2.6	1.9	3.4	0.7	0.7	0.9	1.0		1.0
<b>2023 Ford F-150</b>	2.7	3.8	0.7	11.3	11.1	10.3	4.3	6.7	3.8	2.5	3.0	1.6	1.2	3.4		4.0
<b>2019 Ford Fusion</b>	0.7	0.9	0.4	3.2	2.8	1.9	2.8	1.4	1.1	0.7	0.5	0.4	0.4	0.6	0.5	0.5
<b>2022 Hyundai Tucson</b>	1.2	1.6	0.6	3.7	3.6	3.1	1.9	2.0	1.5	1.1	0.5	0.5	0.4	0.7	0.7	0.7
<b>2022 Subaru Outback</b>	1.4	1.4	0.7	7.8	7.8	5.4	2.4	3.8	2.8	1.9	1.6	1.0	1.0	2.3		2.5
<b>2022 Tesla Model 3</b>	0.8	1.0	0.3	3.9	4.0	5.6	4.6	1.1	0.9	0.7	0.4	0.4	0.3	0.4	0.5	0.5
<b>2022 Toyota Camry</b>	1.0	1.1	0.6	3.6	3.5	3.5	2.0	2.1	1.7	1.2	1.0	0.9	0.6	1.6	0.6	1.7

*Table 11. Laboratory Illuminance Data at OEM Vertical Aim Angle Target - Test Locations at or Below the Horizontal*

Test Vehicles	Test Point Illuminance Values in lux												
	8	9	10	11	12	13	14	15	16	17	18	19	20
<b>2022 Chevrolet Equinox</b>	67.4	58.7	15.6	32.7	20.0	90.3	79.1	95.8	62.0	66.1	263.6	123.6	117.9
<b>2023 Ford F-150</b>	164.0	16.1	18.9	33.2	18.1	85.1	45.8	61.2	23.8	32.6	115.4	40.8	59.7
<b>2019 Ford Fusion</b>	40.6	19.4	10.2	22.8	11.7	56.8	17.5	41.0	7.7	12.4	62.1	12.3	23.6
<b>2022 Hyundai Tucson</b>	77.3	14.8	41.2	68.4	61.4	210.3	177.6	255.4	91.2	160.3	388.2	123.5	286.5
<b>2022 Subaru Outback</b>	92.1	33.8	29.3	44.3	19.7	91.3	57.2	78.0	38.0	43.3	179.2	57.7	81.7
<b>2022 Tesla Model 3</b>	27.6	25.6	19.1	46.1	29.9	107.0	81.2	166.8	52.0	139.2	283.9	117.7	154.9
<b>2022 Toyota Camry</b>	223.7	111.3	37.6	58.5	40.7	104.4	101.1	116.6	58.1	60.1	187.7	122.9	123.0

## Comparison of On-Vehicle Measurements to Lab Measurements

In the comparisons that follow, the lab measurement was considered to be the true value because it was measured using the known test method. To compare the two test methods, the relative difference was calculated between the values measured using each test method. The relative difference was calculated by the following formula:

$$D_{\%} = \frac{E_{on-vehicle} - E_{lab}}{E_{lab}} \times 100$$

Where  $D_{\%}$  is the relative difference,  $E_{Lab}$  is the illuminance value at the test location from the lab data, and  $E_{on-vehicle}$  is the illuminance value measured during on-vehicle testing.

The difference between the illuminance measured in the lab and on-vehicle varied with test vehicle. As Table 12 shows, for the 2022 Chevrolet Equinox and the 2022 Hyundai Tucson, there was minimal difference between the simple average illuminance measured in the lab and on-vehicle. However, for the 2019 Ford Fusion and the 2022 Subaru Outback, there were substantial differences between the average illuminance measured in the lab and on-vehicle.

*Table 12. Average Illuminance for All Seven Test Vehicles*

Test Vehicle	Lab Measured Illuminance (lux)	On-Vehicle Illuminance (lux)	Absolute Difference (lux)	Relative Difference (%)
2022 Chevrolet Equinox	40.43	39.67	-0.76	-2
2023 Ford F-150	28.03	32.46	4.43	16
2019 Ford Fusion	12.31	18.02	5.71	46
2022 Hyundai Tucson	68.27	68.64	0.37	1
2022 Subaru Outback	31.76	41.38	9.62	30
2022 Tesla Model 3	44.02	50.53	6.51	15
2022 Toyota Camry	47.36	40.76	-6.60	-14

Tables 13 and 14 examine the relative differences between the on-vehicle and lab methods for each tested vehicle for each test point or subpoint. To more easily view the data, test locations have been split between those above the horizontal (Table 13), and those at or below the horizontal (Table 14).

The bottom four rows of Tables 13 and 14 show the minimum, maximum, and average of the relative differences from all seven test vehicles for each test point or subpoint. The average relative difference was calculated in two ways. The Average row contains the arithmetic average of the seven test vehicles relative difference values for each test point or subpoint. The absolute average row contains the arithmetic average of the absolute value of the seven test vehicles relative difference values for each test point or subpoint.

Table 13. Relative Difference as a Percentage for Points Above the Horizontal

Test Vehicle	Relative Difference in Percent															
	1	2	3	4a	4b	4c	4d	5a	5b	5c	6a	6b	6c	7a	7b	7c
<b>2022 Chevrolet Equinox</b>	32	52	104	16	24	39	4	0	12	-22	81	55	-3	10		27
<b>2023 Ford F-150</b>	42	2	85	37	62	69	126	55	62	48	93	106	45	49		45
<b>2019 Ford Fusion</b>	93	-11	86	9	0	31	217	87	94	223	112	61	128	0	-11	-8
<b>2022 Hyundai Tucson</b>	47	-22	25	12	10	-10	-40	19	37	69	44	46	42	24	-24	7
<b>2022 Subaru Outback</b>	21	-7	32	8	-5	-16	-33	20	35	16	65	83	11	19		-47
<b>2022 Tesla Model 3</b>	74	22	285	24	8	-40	-9	168	178	161	203	142	87	95	135	135
<b>2022 Toyota Camry</b>	39	-5	38	33	23	-8	-16	28	22	34	42	37	23	-5	-11	-18
<b>Minimum</b>	21	-22	25	8	-5	-40	-40	0	12	-22	42	37	-3	-5	-24	-47
<b>Maximum</b>	93	52	285	37	62	69	217	168	178	223	203	142	128	95	135	135
<b>Average</b>	50	4	93	20	17	9	35	54	63	75	91	76	47	28	22	20
<b>Absolute Average</b>	50	17	93	20	19	30	64	54	63	82	91	76	48	29	26	41

Table 14. Relative Difference as a Percentage for Points at or Below the Horizontal

Test Vehicles	Relative Difference in Percent												
	8	9	10	11	12	13	14	15	16	17	18	19	20
<b>2022 Chevrolet Equinox</b>	26	-44	-8	-5	45	-26	11	-11	10	-25	3	16	-14
<b>2023 Ford F-150</b>	25	1	-2	-21	60	0	64	-22	56	-24	8	46	-19
<b>2019 Ford Fusion</b>	59	119	-34	5	121	-6	145	-52	76	-25	138	90	-27
<b>2022 Hyundai Tucson</b>	28	204	-21	16	-9	0	28	-25	49	-39	15	51	-45
<b>2022 Subaru Outback</b>	311	7	-21	31	112	-24	26	-30	27	-28	-9	49	-37
<b>2022 Tesla Model 3</b>	255	77	43	76	150	68	12	-30	143	-50	-9	42	-38
<b>2022 Toyota Camry</b>	-50	-80	-16	28	17	30	11	-36	5	-32	24	-2	-31
<b>Minimum</b>	-50	-80	-34	-21	-9	-26	11	-52	5	-50	-9	-2	-45
<b>Maximum</b>	311	204	43	76	150	68	145	-11	143	-24	138	90	-14
<b>Average</b>	94	41	-8	19	71	6	42	-30	52	-32	24	42	-30
<b>Absolute Average</b>	108	76	20	26	73	22	42	30	52	32	30	42	30

Table 13 and Table 14 show that the relative difference between on-vehicle and lab testing was large for many test vehicle and test point/subpoint combinations. The highest relative difference was 311 percent for Test Point 8 for the 2022 Subaru Outback. The lowest relative difference was -80 percent for Test Point 9 for the 2022 Toyota Camry. There was a large amount of variability in relative difference from test vehicle to test vehicle and from test point/subpoint to test point/subpoint.

The average relative difference over all test vehicles and measurement locations was 34 percent. The problem with the straight arithmetic average of the relative value is that test vehicle and measurement location combinations with a negative average relative difference cancel out some portion of the contribution of test vehicle and measurement locations combinations with a positive average relative difference. Therefore, to give a better idea of the magnitude of the relative difference at each test vehicle and test point/subpoint combination, the absolute average row was calculated. The absolute average relative difference, calculated over all test vehicles and measurement locations, was 48 percent.

## On-Vehicle Test Procedure Repeatability Results

This section summarizes results from repeatability testing performed using the candidate lower beam headlighting system performance on-vehicle test procedure. The illuminance produced by the 2022 Toyota Camry’s headlamps was measured using the candidate test procedure five times, each time on a different night. Using the measurements from the five nights, the coefficient of variation (CV) was calculated for each measurement location. The CV was calculated by the following formula:

$$CV_{\%} = 100 \frac{\sigma}{\bar{X}}$$

Where  $\sigma$  is the standard deviation of values and  $\bar{X}$  is the mean of values.

The CV scores were categorized according to Table 15.

*Table 15. CV Value Ranges*

CV
0 < x <= 2.5 %
2.5 < x <= 5 %
5 < x <= 7.5 %
7.5 < x <= 10 %
x > 10%

Table 16 and Table 17 show the illuminance measured for each repetition. To more easily view the data, test locations have been split between those above (Table 16), and those at or below the horizontal (Table 17).

The bottom five rows of Table 16 and Table 17 contain descriptive statistics about the 2022 Toyota Camry repeatability data. Shown are the Minimum, Maximum, Average, Standard Deviation, and CV calculated from data collected during the five repeated tests of 2022 Toyota Camry. (Note that unlike all the other data in Table 16 and Table 17, the CV is in percentage and not in lux.)

The CV is a measure of variability expressed as a percentage of the mean. CV is a dimensionless measure of data spread calculated by dividing the standard deviation by the mean value and then multiplying by 100 to convert it to a percentage. CV is calculated according to the formula on the next page.

Table 16. 2022 Toyota Camry Repeatability Illuminance Data at Nominal Vertical Aim Angle - Test Locations Above the Horizontal

Test Repetition	Test Point or Subpoint Illuminance Values in lux															
	1	2	3	4a	4b	4c	4d	5a	5b	5c	6a	6b	6c	7a	7b	7c
Repetition #1	1.4	1.2	0.7	5.1	4.6	3.3	1.7	3.1	2.3	1.7	1.6	1.4	0.8	1.8	1.7	1.7
Repetition #2	1.2	1.0	0.8	4.5	4.1	3.0	1.6	2.6	2.0	1.5	1.3	1.3	0.7	1.5	1.4	1.3
Repetition #3	1.4	1.0	0.8	4.7	4.3	3.2	1.6	2.7	2.0	1.6	1.2	1.2	0.7	1.4	1.5	1.3
Repetition #4	1.3	1.1	0.8	4.6	4.1	3.1	1.8	2.6	2.1	1.6	1.2	1.1	0.7	1.3	1.3	1.2
Repetition #5	1.4	1.0	0.8	4.8	4.4	3.3	1.7	2.8	2.2	1.6	1.5	1.3	0.7	1.6	1.6	1.5
Minimum	1.2	1.0	0.7	4.5	4.1	3.0	1.6	2.6	2.0	1.5	1.2	1.1	0.7	1.3	1.3	1.2
Maximum	1.4	1.2	0.8	5.1	4.6	3.3	1.8	3.1	2.3	1.7	1.6	1.4	0.8	1.8	1.7	1.7
Average	1.3	1.1	0.8	4.7	4.3	3.2	1.7	2.7	2.1	1.6	1.4	1.3	0.7	1.5	1.5	1.4
Standard Deviation	0.1	0.1	0.0	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.2
CV (%)	5.5	5.4	4.3	4.2	4.4	3.1	4.2	6.4	5.4	4.0	10.7	7.6	5.6	9.9	9.8	11.8

*Table 17. 2022 Toyota Camry Repeatability Illuminance Data at Nominal Vertical Aim Angle -  
Test Locations at or Below the Horizontal*

Test Vehicle	Test Point Illuminance Values in lux												
	8	9	10	11	12	13	14	15	16	17	18	19	20
<b>Repetition #1</b>	224.1	32.4	27.5	71.4	47.4	115.5	105.7	73.5	61.2	40.5	217.9	116.5	79.7
<b>Repetition #2</b>	68.2	18.8	29.4	77.1	48.0	144.8	111.8	74.9	61.6	41.3	234.6	123.4	85.2
<b>Repetition #3</b>	86.6	19.4	34.5	76.7	48.9	145.3	116.6	77.8	62.3	41.2	240.9	122.5	87.9
<b>Repetition #4</b>	57.9	18.5	32.3	75.6	46.6	143.7	117.0	74.1	59.3	39.6	240.0	121.0	85.3
<b>Repetition #5</b>	118.0	21.7	34.7	73.8	46.3	131.2	109.8	74.1	60.2	41.0	234.0	117.3	88.1
<b>Minimum</b>	57.9	18.5	27.5	71.4	46.3	115.5	105.7	73.5	59.3	39.6	217.9	116.5	79.7
<b>Maximum</b>	224.1	32.4	34.7	77.1	48.9	145.3	117.0	77.8	62.3	41.3	240.9	123.4	88.1
<b>Average</b>	111.0	22.2	31.7	74.9	47.4	136.1	112.2	74.9	60.9	40.7	233.5	120.1	85.2
<b>Standard Deviation</b>	54.9	4.8	2.6	1.9	0.9	10.5	3.9	1.4	1.0	0.6	7.6	2.5	2.8
<b>CV (%)</b>	54.2	23.6	8.9	2.8	2.0	8.5	3.8	2.0	1.7	1.5	3.6	2.3	3.5

Tables 16 and 17 show that high CV values occurred near the location of the cutoff line. For the nominal vertical aim angle used, the aiming process (prior to data collection) adjusted the cutoff line until it was the same height above the road as the optical center of the headlamps. The two measurement locations at the headlamp horizontal location, measurement locations 8 and 9, had the highest CV values of any test point or subpoint. Subpoints 6a, 6b, 6c, 7a, 7b, and 7c and Test Point 10 had higher CV values.

In terms of test procedure repeatability, the data show that certain test locations have a low level of repeatability due to the nature of the beam pattern. For example, by definition, the area around the cutoff line of a lower beam headlamp is an area of high contrast resulting in a rapid change in light intensity. If test setup or aim has some variability, the points around the cutoff line will be far less repeatable. The repeatability of the lab measurements was not assessed for this effort. However, the specifications for the Sapphire AP-60HD Heavy Duty Goniophotometer used in laboratory measurements reported herein note a positional accuracy of "0.005 degree resolution / 0.01 degree repeatability" indicating a high level of repeatability. This goniometer system performance is superior to measurements produced by the on-vehicle test method, which are affected by pavement smoothness variation, as well as possibly vehicle alignment error and ambient illumination effects (although the method sought to subtract out this effect). The sensors of laboratory quality goniometer systems do not move, and the parts that do move (any components that move or rotate the mounting plate) are highly calibrated and precise. Most variation in the lab-based test method would come from small variation in mounting the lamp to the test fixture or the test fixture to the mounting plate.

## Summary and Conclusions

This report summarizes research conducted to support NHTSA's response to the requirements of the Infrastructure Investment and Jobs Act of 2021 relating to the development of performance-based standards for vehicle headlamp systems to ensure proper headlamp aim and to require testing of headlighting system performance on-vehicle.

Currently, headlighting system photometric performance for FMVSS No. 108 (49 CFR Sec. 571.108, FMVSS No. 108, 2024) is measured at the equipment level. To measure the performance on-vehicle of lower beam headlighting systems, a test method was developed by adapting methods used in previous NHTSA and UMTRI studies. The developed test procedure involved setting illuminance receptor heads at various longitudinal, lateral, and vertical locations on the roadway that were translated from the FMVSS No. 108 photometric test points listed as polar coordinates.

Headlighting system performance of seven test vehicles of MY 2019 or newer was measured to assess the candidate test procedure. The test vehicles were horizontally aligned to the Cartesian coordinates of the test area and illuminance was measured from the combined set of lower beam headlamps aimed to the manufacturers' target aim specification. After all headlighting system performance on-vehicle testing was completed, the headlamps were removed from the test vehicles and sent to an ISO-accredited photometric test lab to be measured. Results for lab-based testing was compared to results from the developed on-vehicle test procedure.

On average, over all seven test vehicles and all measurement locations, the illuminance measured in the lab was 38.96 lux. Illuminance measured in the on-vehicle testing averaged 41.69 lux. On average, the on-vehicle measured illuminance was 7 percent higher than the laboratory measured illuminance, meaning that on average the on-vehicle test method measured illuminance higher than measuring the parts in a lab. The difference between the lab-measured illuminance and on-vehicle illuminance varied substantially across test vehicles.

There was a large relative difference between on-vehicle and lab testing for many test vehicle and test point/subpoint combinations. The highest relative difference was 311 percent and the lowest relative difference was -80 percent. There was a large amount of variability in relative difference from test vehicle to test vehicle and from test point/subpoint to test point/subpoint. The average relative difference over all test vehicles and measurement locations was 34 percent. The absolute average relative difference, calculated over all test vehicles and measurement locations, was 48 percent.

Repeatability testing for the developed on-vehicle test procedure involved performing five full test repetitions with a single test vehicle (2022 Toyota Camry). Analysis of the repeatability test data highlighted the sensitivity of measurements made near a lamp's cutoff line. Results showed that measurement locations closer to the nominal vertical aim angle had much higher coefficients of variation than test locations further from the nominal vertical aim angle.

These results differ from those obtained in NHTSA's 2019 research (Mazzae et al.) to develop an on-vehicle lower beam headlighting system visibility confirmation test procedure, which was found to be effective in characterizing lower beam headlighting system performance levels and had good repeatability. Unlike this effort, measurements obtained using the draft lower beam headlighting system visibility confirmation test procedure were not compared to a known measurement method like lab-based testing. While that testing effectively measured lower beam

headlighting system performance for a selection of measurement locations in an on-vehicle test, it did not attempt to replicate FMVSS No. 108 photometry testing as the current research did. The draft test procedure method also included a smaller number of test locations, most of which correlated to locations in the headlamp beam pattern further from the cutoff line than some points measured in this effort. For this reason, the repeatability was better for the draft test procedure than for the test method used in this effort.

Overall, this effort revealed challenges associated with on-vehicle testing as compared to traditional lab-based measurements for assessing lower beam headlighting system performance. Although the two methods displayed similar trends, the accuracy of the on-vehicle measurements were worse than the lab-based measurements. This work also highlighted the difficulty of precisely repeating test results due to beam patterns' sensitivity to proper headlamp vertical aim. The poor repeatability of the on-vehicle measurements seen during this research reveals the challenges associated with an on-vehicle measurement method as compared to a lab-based method for assessing lower beam headlighting system performance.

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**Appendix A: Konica Minolta T-10a Illuminance Meter Specifications**

<b>Type</b>	Digital illuminance meter with detachable receptor head.
<b>Receptor</b>	Silicon photocell.
<b>Relative Spectral Response (<math>f_1</math>)</b>	The amount of departure from $V(\lambda)$ ... within 6% (CIE).
<b>Cosine Correction Characteristics (<math>f_2</math>)</b>	Within 3%.
<b>Illuminance Units</b>	Lux (lx) or foot-candles (fcd) (switchable)
<b>Range Setting</b>	Auto range (can be switched between five ranges manually).
<b>Measuring Function</b>	NORM: illuminance in lux (lx) or foot-candles (fcd), delta: illuminance difference lx (fcd)/ratio (%), $\Sigma$ : integrated illuminance in lux-hours (lx-h) or foot-candle-hours (fcd-h)/integration time (h) / average illuminance in lux (lx) or foot-candles (fcd).
<b>Measuring Range</b>	0.01 – 299,900 lx /0.001 – 29,990 fcd.
<b>User Calibration Function</b>	Set the color correction factor (CCF): 0.500 to 2.000.
<b>Integrated Illuminance/ Time</b>	0.01 – 999,900 103 lx-h, 0.001 to 99,990 103 fcd-h / 0.001 – 9,999 h
<b>Correction Function</b>	Settable range of the color correction factor (CCF): 0.500 to 2.000.
<b>Linearity</b>	2% $\pm$ 1 digit of value displayed
<b>Temperature Drift</b>	Within 3%.
<b>Humidity Drift</b>	Within 3%.
<b>Computer Interface</b>	Conforms to USB standard.
<b>Printer Output</b>	RS-232C.
<b>Analog Output</b>	1 mV / digit, maximum saturation voltage 3 V, output impedance 10 k $\Omega$ , 90% response time: FAST setting: 1 ms, SLOW setting: 1 s.
<b>Display</b>	3 or 4 significant - digit LCD with back - light illumination.
<b>Operating Temperature/ Humidity Range</b>	-10 to 40 °C, relative humidity 85% or less (at 35 °C) with no condensation.
<b>Storage Temperature/ Humidity Range</b>	-20 to 55 °C, relative humidity 85% or less (at 35 °C) with no condensation.
<b>Power</b>	AA-size batteries (x2) / AC adapter (optional).
<b>Battery Life</b>	72 hours or longer (when alkaline batteries are used for continuous measurement).
<b>Dimensions</b>	69 $\times$ 174 $\times$ 35 mm.
<b>Weight</b>	200 g without batteries.
<b>Standard Accessories</b>	Batteries, case, cap, strap.

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