

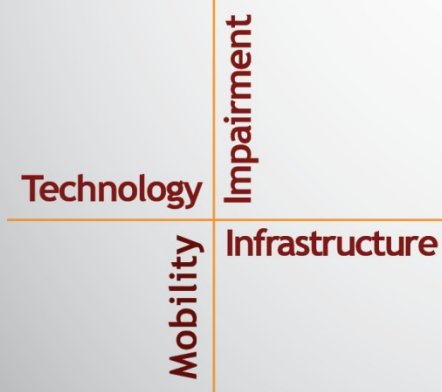
NSTSCCE

National Surface Transportation
Safety Center for Excellence

Development of a Mobile Measurement System for Roadway Lighting

Ronald B. Gibbons • Jason Meyer • Christopher J. Edwards

Submitted: January 4, 2018



Housed at the Virginia Tech Transportation Institute
3500 Transportation Research Plaza • Blacksburg, Virginia 24061

ACKNOWLEDGMENTS

The authors of this report would like to acknowledge the support of the stakeholders of the National Surface Transportation Safety Center for Excellence (NSTSCE): Tom Dingus from the Virginia Tech Transportation Institute, John Capp from General Motors Corporation, Chris Hayes from Travelers Insurance, Martin Walker from the Federal Motor Carrier Safety Administration, Lincoln Cobb from the Federal Highway Administration, and Cathy McGhee from the Virginia Department of Transportation and the Virginia Transportation Research Council.

The NSTSCE stakeholders have jointly funded this research for the purpose of developing and disseminating advanced transportation safety techniques and innovations.

EXECUTIVE SUMMARY

In recent years, the complexity of the evaluation metrics of roadway lighting has continually increased. In order to measure the effectiveness of a roadway lighting system in situ, a mobile measurement system has been developed to provide evaluations of illuminance, luminance, spectral content, glare, human visibility performance, and vehicle condition. This system, the Roadway Lighting Mobile Measurement System (RLMMS), has been developed to be transportable to anywhere in the world and mounted on any vehicle.

The RLMMS consists of five illuminance meters: four measure the centerline and wheel path illuminance of the vehicle and the fifth measures the illuminance at the eye of the driver. The system also uses two cameras: the first a calibrated luminance camera and the second a color camera for scene evaluation. The RLMMS is able to tie into the internal vehicle network to obtain speed and distance measurements. Additional tools, such as a spectroradiometer and an eye tracker, have also been incorporated into the system. Finally, as a method of evaluating human response, the RLMMS includes buttons that allow users to place response markers in the data stream.

The repeatability and reproducibility of the system was evaluated, and comparisons were made to the traditional handheld method of measuring illuminance. Results indicate that the system's measurement of illuminance may be considered acceptable. The entire system has been programmed in LabView and allows for a variety of configurations of data collection. The system has been utilized in several research projects, including some in Anchorage, Alaska; Honolulu, Hawaii; and San Diego, California.

TABLE OF CONTENTS

LIST OF FIGURES.....	v
LIST OF TABLES.....	vii
LIST OF ABBREVIATIONS.....	ix
CHAPTER 1. INTRODUCTION.....	1
SYSTEM DESIGN.....	1
CHAPTER 2. EQUIPMENT.....	3
ILLUMINANCE METERS.....	3
GPS.....	3
LUMINANCE CAMERA.....	4
COLOR CAMERA.....	4
VEHICLE CONTROLLER AREA NETWORK.....	4
SPECTRORADIOMETER.....	4
EYE TRACKER.....	4
BUTTON BOXES.....	5
DATA ACQUISITION SYSTEM.....	5
CHAPTER 3. SYSTEM USAGE.....	7
CHAPTER 4. REPEATABILITY AND REPRODUCIBILITY.....	9
EXPERIMENTAL DESIGN.....	9
EQUIPMENT.....	10
PROCEDURE.....	10
DATA ANALYSIS.....	11
RESULTS.....	11
CHAPTER 5. COMPARISON TO HANDHELD MEASUREMENTS.....	17
CHAPTER 6. SUMMArY AND CONCLUSIONS.....	19
REFERENCE.....	20

LIST OF FIGURES

Figure 1. Diagram. Roadway Lighting Mobile Monitoring System (RLMMS).....	3
Figure 2. Photo. Sample luminance camera image.....	4
Figure 3. Photo. ViewPoint eye tracker hardware.....	5
Figure 4. Photo. RLMMS components mounted on and inside a vehicle.....	6
Figure 5. Graph. Sample illuminance data from the RLMMS.....	7
Figure 6. Map. Route for R&R evaluation.....	9
Figure 7. Chart. R&R results – mean overhead illuminance.....	12
Figure 8. Diagram. Gage R&R results – mean overhead illuminance.....	13
Figure 9. Chart. R&R results – mean glare illuminance.....	14
Figure 10. Diagram. Mean glare illuminance.....	14
Figure 11. Photo. Evaluation area for RLMMS/handheld comparison.....	17
Figure 12. Graph. Comparison of RLMMS to handheld meter.....	18

LIST OF TABLES

Table 1. Data collection requirements.	1
Table 2. Independent variables – R&R evaluation.....	10
Table 3. Lighting sections descriptions.	10
Table 4. R&R evaluation procedure.	11

LIST OF ABBREVIATIONS

AIAG	Automotive Industry Action Group
fps	frames per second
GPS	Global Positioning System
HPS	high pressure sodium
MH	metal halide
NSTSCE	National Surface Transportation Safety Center for Excellence
R&R	repeatability and reproducibility
RLMMS	Roadway Lighting Mobile Measurement System
VTTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

Consideration of the entire visual scene is vital to ongoing evaluation of roadway lighting. Roadway lighting design is typically performed in silos, meaning that roadway lighting levels are established without consideration of the other components of the visual scene, such as off-right-of-way lighting and commercial lighting. Evaluation of a lighting installation requires consideration of all of these factors. As a research tool, a measurement system was required to evaluate the entire visual scene. In order to typically evaluate an entire scene, one would need to manually walk the area and place illuminance meters at multiple points to collect data. The downside to such an approach is that it typically takes a much longer time to do such an evaluation by hand. This is especially the case if one were to attempt to evaluate a large area of roadway that could extend for miles. This need for a system that is able to take such measurements quickly and over a large area led to the development of the Roadway Lighting Mobile Measurement System (RLMMS). The RLMMS, initially sponsored by the National Surface Transportation Safety Center for Excellence (NSTSC), has been developed at the Virginia Tech Transportation Institute (VTTI) by the Lighting and Infrastructure Technology Group, and has been used in several in situ evaluations.

One of the requirements of this system was determined to be mobility and portability. It had to be possible to install the RLMMS on a vehicle at any location in the world and provide accurate and reliable data.

This system was developed in two versions. This first version measured illuminance only, whereas the second version measures human response, luminance, spectral metrics, and links to the vehicle network to provide speed and driver performance inputs.

SYSTEM DESIGN

The data types of interest and the selected information sources are shown in Table 1.

Table 1. Data collection requirements.

Data Type	Source
Luminance of the roadway and the visual environment	Luminance camera
Color scene image	Color camera
Vehicle speed	Vehicle J1850 network
Distance	Vehicle J1850 network
Vehicle location	GPS
Roadway illuminance	Illuminance meter network
Vertical illuminance at the windshield as a metric of glare	Illuminance meter
Spectral power distribution of the environment	Portable spectroradiometer
Driver/passenger response	In-vehicle button box

CHAPTER 2. EQUIPMENT

The system layout is shown in Figure 1. The Global Positioning System (GPS) unit and the illuminance meter network are placed on the roof of the vehicle on an aluminum frame, which is attached using suction cups. Inside the windshield, also attached with suction cups, are the color camera, the luminance camera, and the vertical illuminance meter.

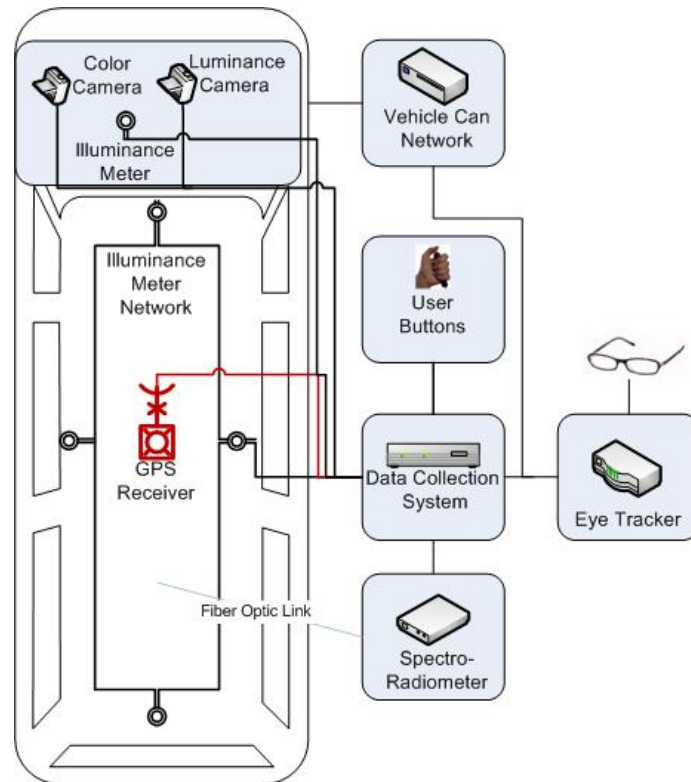


Figure 1. Diagram. Roadway Lighting Mobile Monitoring System (RLMMS).

ILLUMINANCE METERS

Five Minolta T-10 illuminance meters were attached to the data collection box through networked cables. Four of the illuminance meters were horizontally mounted directly to the roof of the vehicle in such a way that two illuminance meters were positioned over the right and left wheel paths and the other two meters were placed along the centerline of the vehicle. An additional vertically mounted illuminance meter was positioned inside the vehicle windshield.

GPS

A NovaTel GPS device was positioned on the vehicle roof in the center of the horizontally mounted illuminance meters. The GPS device was directly connected to the data collection box and provided latitude and longitude measurements to be used in the analysis process.

LUMINANCE CAMERA

The Luminance Camera is a system developed by the VTTI Lighting and Infrastructure Technology Group, with funding from NSTSCE, which allows for a calibrated data collection of the visual scene from a moving vehicle. This system is controlled such that the gain and shutter speed of the camera are changed to manipulate the responsiveness of the system to the environment. This camera is capable of capturing 7 frames per second (fps) as a vehicle drives. The images provided are 12 bit 1600×1200 images of the environment. A sample image is shown in Figure 2.



Figure 2. Photo. Sample luminance camera image.

COLOR CAMERA

The color scene camera is a Point Grey Flea camera which provides a $1,280 \times 960$ RGB image. Like the luminance camera, this system is capable of capturing 7 fps.

VEHICLE CONTROLLER AREA NETWORK

The vehicle network is an in-vehicle network which provides information about the vehicle's behavior. For the RLMMS, vehicle speed and throttle position are captured. The vehicle network is attached to the data acquisition system through a standard interface from National Instruments.

SPECTRORADIOMETER

To capture spectroradiometric data, an Ocean Optics HR4000 spectroradiometer is mounted inside the vehicle with a fiber optic link to an integrating sphere collector on the vehicle roof. This system allows for the capture of the lamp spectrum from 250 to 1,050 nm.

EYE TRACKER

The eye tracker used for this system is a ViewPoint EyeTracker, with EyeFrame hardware, by Arrington Research, Inc. The Viewpoint Eyetracker consists of both hardware and software components in an effort to capture and analyze eye movements. The eye-tracking hardware

components are mounted to lightweight goggles that fit a variety of participant head sizes. Attached to the goggles are two small eye-tracking cameras and two small infrared light-emitting diode (LED) illuminators that point toward each eye (see Figure 3). There is one camera and one LED illuminator per eye, both of which can be adjusted in order to capture an image of the pupil. A third camera is mounted in the center of the forehead above the eyes to capture the forward scene via video. For our purposes, the scene camera captures objects within the driver's forward field of view, including the vehicle interior and forward roadway. The goggles allow participants to view any part of the scene, as there is no restriction in head movement. All of the cameras are connected to a PC through a frame grabber card.



Figure 3. Photo. ViewPoint eye tracker hardware.

The PC also contains the ViewPoint calibration and analysis eye tracker software. The pupil information is captured via the eye cameras using a dark pupil infrared capture method. When the pupils have been located via the eye cameras, the participant's settings are then calibrated relative to the pixels of a charge coupled device array (a multichannel array detector of ultraviolet, visible and near-infra light).

The RLMMS is linked to the data acquisition system on the PC via an Ethernet port. Timing messages are sent from the RLMMS to synchronize the two data acquisition systems.

BUTTON BOXES

A small square box with an illuminated push button (a "button box") for each of the participants is mounted inside the vehicle. The user simply pushes a button and the event (such as detection of a pedestrian in the roadway) is recorded in the data acquisition system.

DATA ACQUISITION SYSTEM

The RLMMS hardware is connected to the data acquisition system and controlled by a specialized software program created in LabVIEW™. The entire hardware suite is synchronized through the software program and data collection rates are set at 20 Hz. Video image capture rates are typically set at 3.75 fps. The final output file used during the analysis contained a synchronization stamp, GPS information (e.g., latitude and longitude), button presses, individual images from each of the cameras inside the vehicle, the illuminance meter data from each of the

Minolta T-10s, the vehicle information, and a spectrum file. The data acquisition system actually consists of three computers linked with an Ethernet network. Each of the color and luminance cameras has a dedicated computer to ensure proper data collection, which is triggered by the master data acquisition system that captures all of the other data.

The hardware mounted on a vehicle (the “spider” apparatus) is shown in Figure 4. Here the illuminance and GPS receiver can be seen on the vehicle roof, and the cameras and illuminance meters are seen inside the windshield.



Figure 4. Photo. RLMMS components mounted on and inside a vehicle.

CHAPTER 3. SYSTEM USAGE

The system has been used in several investigations thus far. The first system version was used in the lighting evaluation of the installation on the Minneapolis-St. Paul I-35 Bridge. The second version has been used in human factors studies based in Anchorage, Alaska, and San Diego, California.

As an example, the results of the data collection from the Minneapolis-St. Paul Bridge are shown in Figure 5. Here, the illuminance from each of the luminaires in each of the five lanes is plotted. This was performed for both northbound and southbound directions. It is expected that these measurements will be taken every 3–6 months to monitor the changes in the lighting system on the bridge. This project has allowed us to monitor the performance of the LED system over a long period of time to establish the LED system-associated design factors related to dirt and system output changes.

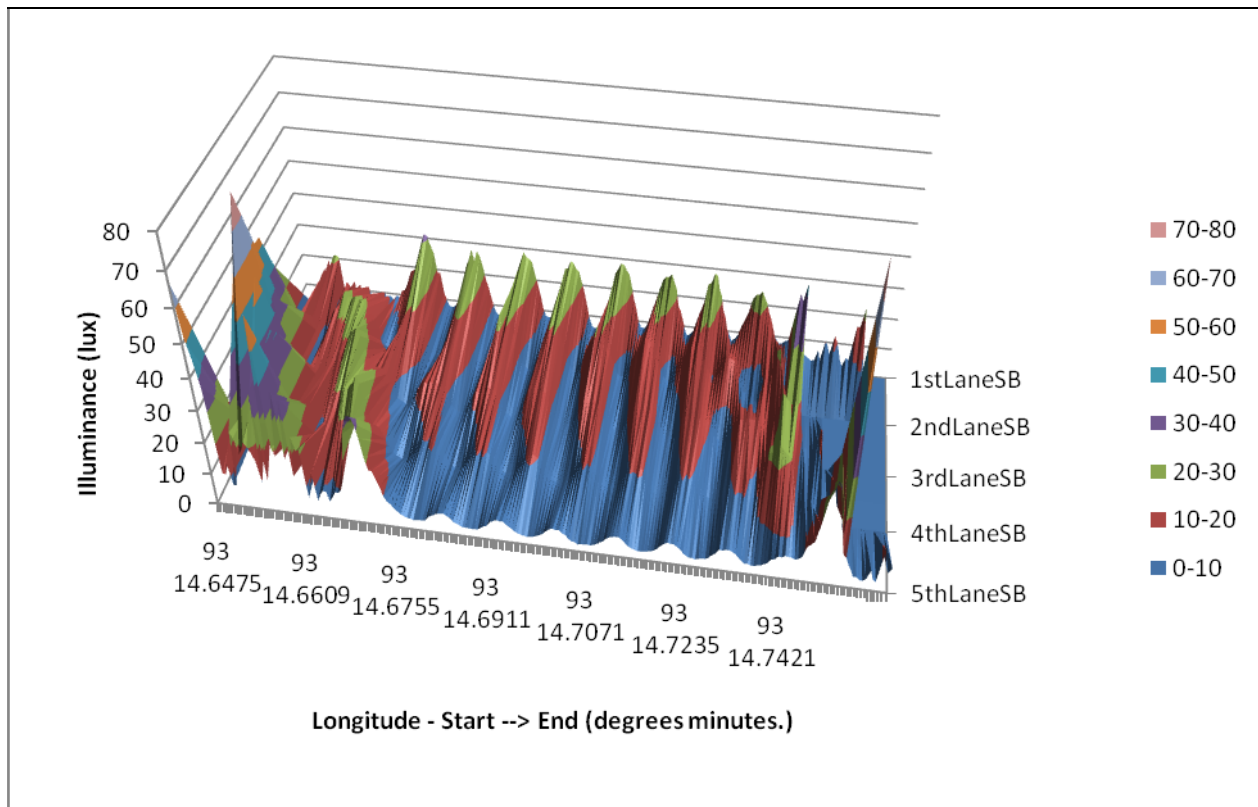


Figure 5. Graph. Sample illuminance data from the RLMMS.

CHAPTER 4. REPEATABILITY AND REPRODUCIBILITY

EXPERIMENTAL DESIGN

A repeatability and reproducibility (R&R) evaluation was undertaken to account for the level of data consistency over time (repeatability) and among different users (reproducibility). Results are presented based on the Automotive Industry Action Group (AIAG) satisfactory variance below 10%.⁽¹⁾

The gauge R&R evaluation was conducted with a driving route mapped out to be driven by multiple operators (Figure 6). Operators were also tasked to set up the RLMMS multiple times. This included dismantling the “spider” apparatus containing the illuminance sensors, as well as the glare illuminance sensor, and luminance and color cameras.

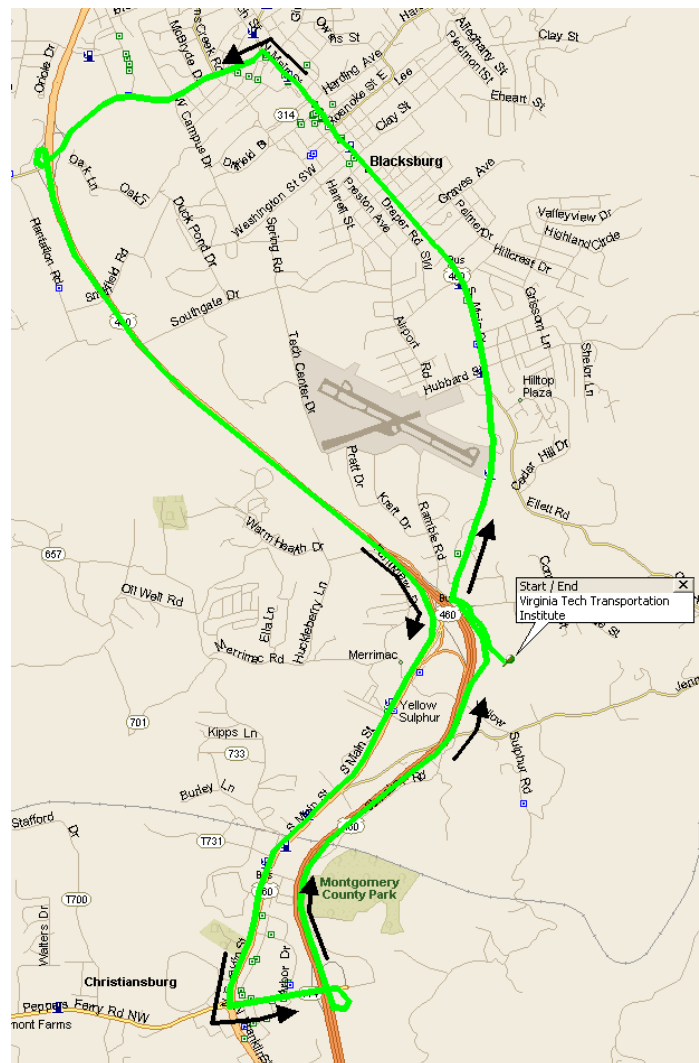


Figure 6. Map. Route for R&R evaluation.

Three different pairs of individuals operated a vehicle equipped with the RLMMS during this R&R evaluation. The environment was a predetermined route to measure the consistency of data being collected by the system. Manipulated variables are shown in Table 2. The variable number of drivers was important for the evaluation in order to understand if the system was obtaining reproducible data regardless of the driver of the vehicle or the slight variations in setup of the illuminance sensor “spider” apparatus. The route was divided into six sections that ranged from a downtown area to a highway area. Within these six sections, specific subsections were isolated in order to make clearer comparisons between lighting types of different roadway types. For example, Section 1 is a 1.4-mile portion of the route, but Section 1a is a specific section of the route at the entrance to a downtown establishment. Lighting sections were selected based on the type of overhead lighting in the environment. The two lighting types were high pressure sodium (HPS) and metal halide (MH). Brief descriptions of the lighting sections are in Table 3. Dependent measures included average overhead luminaire illuminance values and glare illuminance recorded by the RLMMS, as well as luminance and color data.

Table 2. Independent variables – R&R evaluation.

Variable	Levels
Operators	1,2,3
Lighting Sections	Lighting 1a, 1b, 1c, 2a, 3a, 4a, 5a, 6a

Table 3. Lighting sections descriptions.

Lighting Section	Description
1a	Entering downtown (HPS)
1b	Downtown commercial (HPS)
1c	Downtown commercial/residential (HPS)
2a	Downtown commercial (MH)
3a	Leaving downtown residential (HPS)
4a	Highway (HPS)
5a	Intersection (HPS)
6a	Highway (no lighting)

EQUIPMENT

The vehicle used for the R&R evaluation was a 2002 Cadillac Escalade with the RLMMS mounted. The route taken by operators during this evaluation is pictured in Figure 6, above.

PROCEDURE

Three pairs of operators were asked to position the RLMMS on the vehicle. Following a measurement of the ambient illuminance, the predetermined route was driven three times without making adjustments to the RLMMS’s positioning. This was undertaken in an effort to determine the level of variation in data due to the environment itself. This variation, known as parts variation, can then be taken into account in isolating the variation in data collected by an operator over multiple setups of the RLMMS (repeatability) as well as data collected by different

operators (reproducibility). Following the initial three laps of the route, the RLMMS was dismantled and remounted on the vehicle by the same operator. The route was driven again and then the RLMMS was dismantled two additional times. This procedure was then duplicated with two additional pairs of operators over the course of three nights. A diagram of this procedure is shown below in Table 4.

Table 4. R&R evaluation procedure.

Night 1 (Reproducibility)	Night 2 (Reproducibility)	Night 3 (Reproducibility)
Operator 1 drive route	Operator 2 drive route	Operator 3 drive route
Operator 1 drive route	Operator 2 drive route	Operator 3 drive route
Operator 1 drive route	Operator 2 drive route	Operator 3 drive route
Operator 1 dismantle RLMMS and reposition	Operator 2 dismantle RLMMS and reposition	Operator 3 dismantle RLMMS and reposition
Operator 1 drive route (Repeatability)	Operator 2 drive route (Repeatability)	Operator 3 drive route (Repeatability)
Operator 1 dismantle RLMMS and reposition	Operator 2 dismantle RLMMS and reposition	Operator 3 dismantle RLMMS and reposition
Operator 1 drive route (Repeatability)	Operator 2 drive route (Repeatability)	Operator 3 drive route (Repeatability)
Operator 1 dismantle RLMMS and reposition	Operator 2 dismantle RLMMS and reposition	Operator 3 dismantle RLMMS and reposition
Operator 1 drive route (Repeatability)	Operator 2 drive route (Repeatability)	Operator 3 drive route (Repeatability)

DATA ANALYSIS

Results of the system’s R&R evaluation are presented based on the AIAG satisfactory variance below 10%.⁽¹⁾ Gauge R&R evaluations were conducted in JMP SAS.

RESULTS

The results of the RLMMS R&R evaluation are shown below in Figure 7. Values displayed in the chart are the mean illuminance values (lux) grouped first by operator, followed by the different lighting sections (Table 3) inside the data collection area. The illuminance values represented are those recorded during the “repeatability” runs—the final three runs driven by each operator (Table 4). As Figure 7 shows, the mean illuminance values within each lighting section varied among different runs of the route, but this variation was comparable across the different operators.

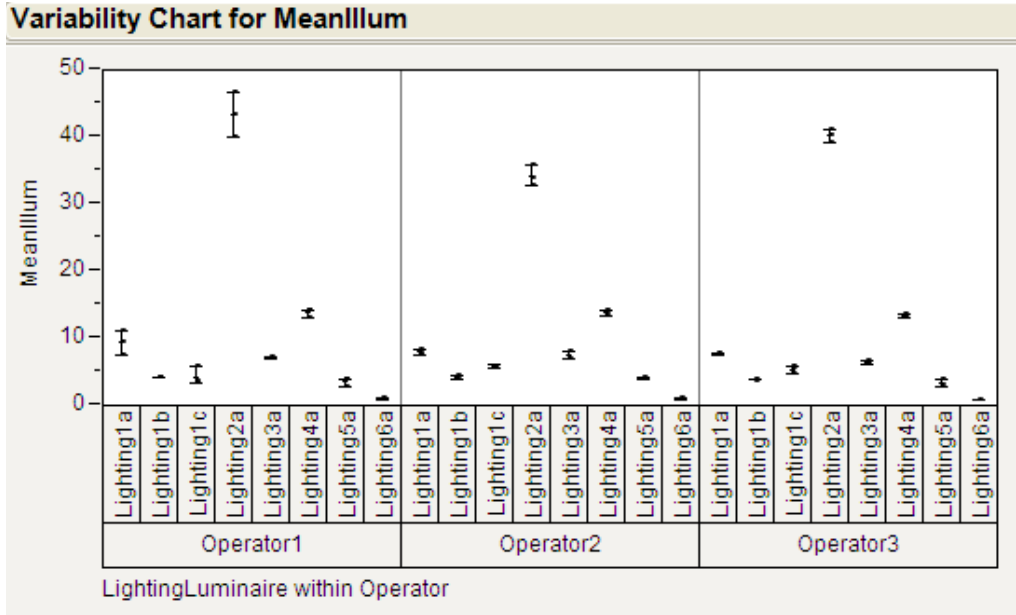


Figure 7. Chart. R&R results – mean overhead illuminance.

In order to determine if this level of variability within each operator’s driving of the route was due to the RLMMS or due to the inherent variability of the parts (the luminaires themselves), a specific R&R analysis was conducted. This was intended to pinpoint the percentage of variability in the results that could be attributed to the parts (in this case, the luminaires) and what could be attributed to the system being used to collect the data (in this case, the RLMMS and its operators). The results of this analysis are displayed in Figure 8. The percentage of variability attributed to the RLMMS has been isolated in the figure as the gauge R&R value.

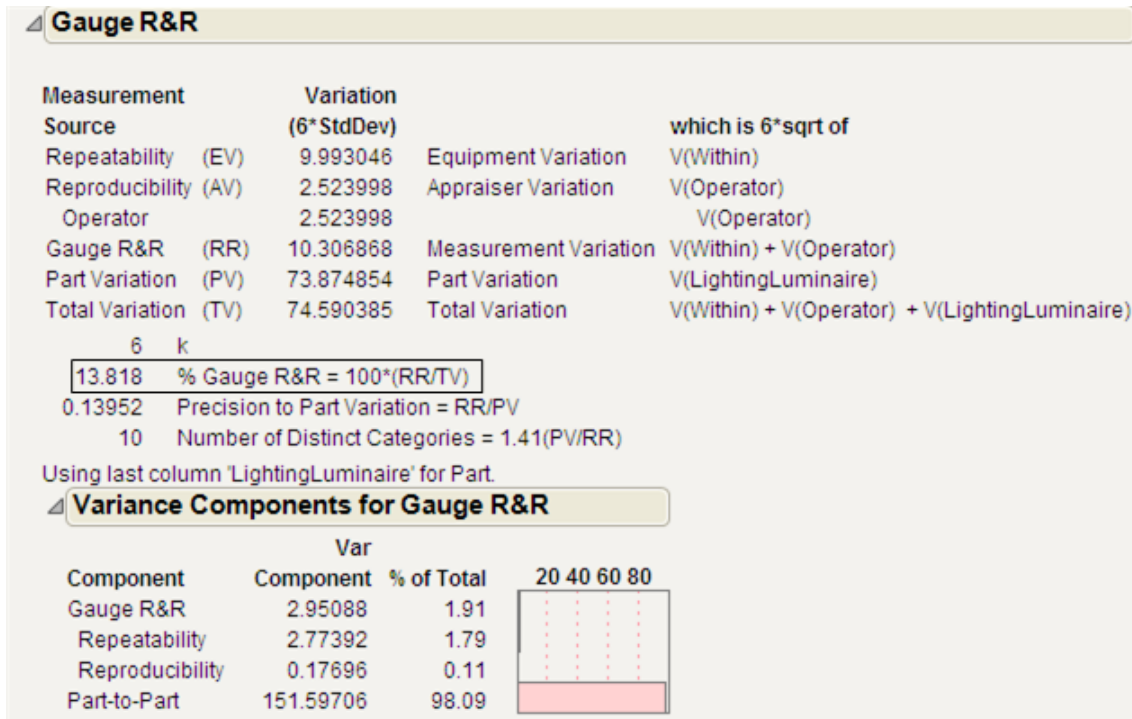


Figure 8. Diagram. Gage R&R results – mean overhead illuminance.

The results above indicate the consistency in the device over time (repeatability) and among different users (reproducibility). The goal would therefore be to keep this percentage of variation at a minimal level. According to AIAG (2002),⁽¹⁾ a percentage of variation is considered “acceptable” below 10%, “may be acceptable” between 10% and 30%, based on associated expenses and importance of application, and “unacceptable” above 30%. Therefore, this percentage of variation found here—13% of the total variation—may be considered acceptable.

In addition to the overhead illuminance as recorded by the rooftop portion of the RLMMS, the glare was also recorded by the vertical illuminance meter mounted inside the windshield area. An R&R analysis was also conducted for this glare measurement device. The resulting mean illuminance values are displayed in Figure 9. Similar to the illuminance recorded by the rooftop portion of the RLMMS, the mean values between operators and within operators were similar, but a more specific investigation into the level of variability was required. This was necessary in order to determine whether the major source of variability was the differences between operators in setting up the glare meter or the differences in the way a single operator set up the glare meter between one test route drive and another.

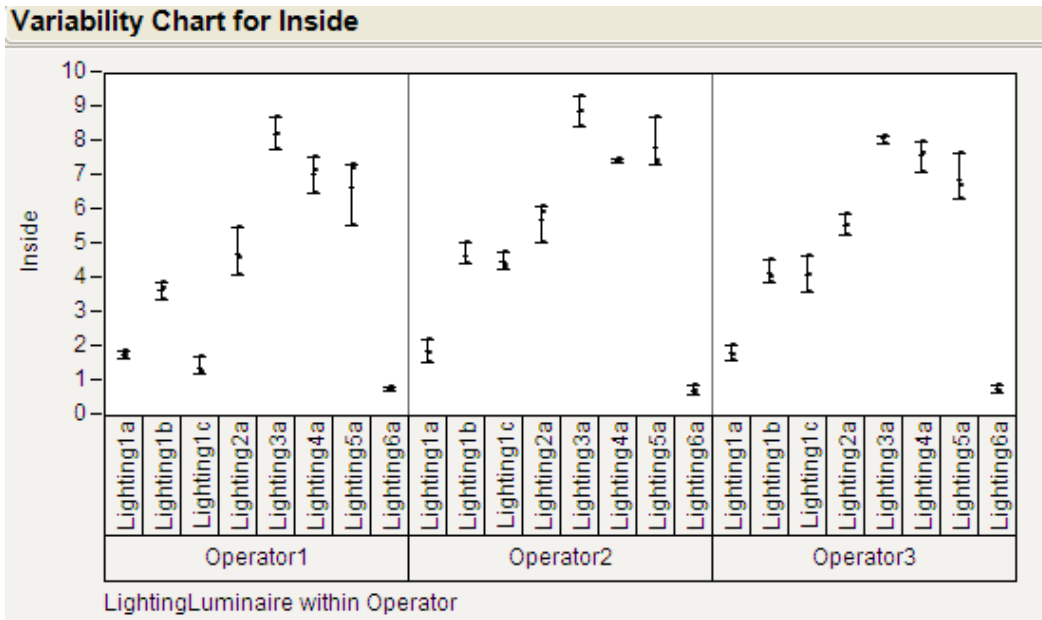


Figure 9. Chart. R&R results – mean glare illuminance.

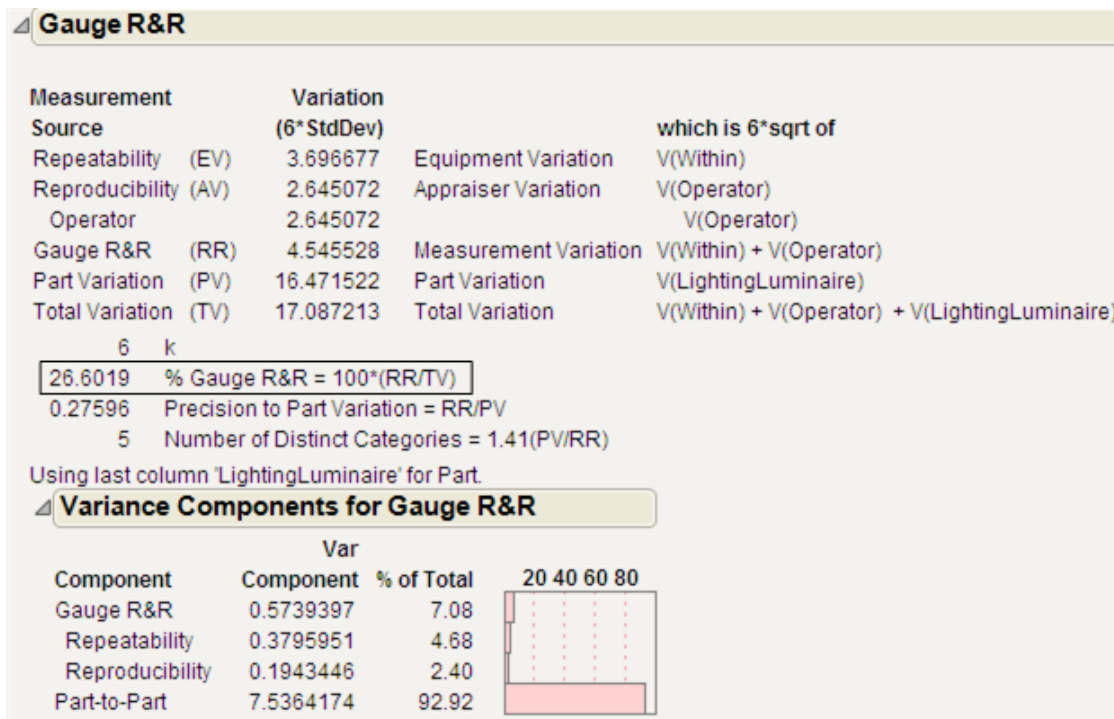


Figure 10. Diagram. Mean glare illuminance.

Results indicated that the percentage of variability that can be attributed to the different users and across different trials was approximately 26%, which is still in the range that “may be acceptable.” There are two possible reasons why this variability was higher in the glare data than in the rooftop data collection. The first reason may be the location of this glare meter. Being inside the windshield area, the glare meter is sensitive to both light from oncoming traffic and

light from existing overhead roadway lighting. This means that the glare meter would be greatly affected by the oncoming traffic's vehicle headlamps (which were not constant between the multiple driving trials). Future development of the RLMMS system will attempt to develop methods for evaluating the effect of headlamps. Additionally, the glare meter detected luminaires at a high angle of incidence when they were effectively overhead of the vehicle, which is not a typical driver experience. To account for this, a shield was developed to match the geometry of the vehicle roof and block the direct glare.

The second reason for the higher percentage of variability in the glare meter as compared to the rooftop apparatus is related to the number of sensors taken into account. The results for the rooftop are based on an average illuminance from four illuminance head sensors mounted on the rooftop. This allows for a more general idea of the light being distributed upon the roadway, while also allowing for future analysis of the different areas for comparison (for example, comparing the light being distributed close to the curb with the "right" illuminance sensor to the light in the middle of the traveling lane with the "front" or "rear" sensors). Because the resulting values take into account averaged amounts, the variability is already reduced as the effects of outlying values become more minimized through averaging. A single instance of a spike in illuminance measurement as recorded by a single sensor will have a minimal impact on the results when values are being averaged together. However, the glare meter is a single sensor on the windshield, and as such measurement results will be much more affected by outlying values. For example, a single instance of an oncoming vehicle with brighter high beams activated will skew the results for that drive compared to results of other drives among other operators where high beams were not encountered.

CHAPTER 5. COMPARISON TO HANDHELD MEASUREMENTS

In addition to the reliability of the system over time, a comparison to the more traditional method of measuring illuminance by means of a handheld illuminance meter was conducted. In order to make this comparison, a vehicle was equipped with the RLMMS and positioned in an area under a single luminaire. The vehicle was positioned under multiple areas under the luminaire in order to evaluate multiple intensities from a single luminaire. This area is pictured below in Figure 11.



Figure 11. Photo. Evaluation area for RLMMS/handheld comparison.

The locations of the right and left sensors for the first data collection location are labeled in the figure. Each of the four sensors was evaluated independently in order to accurately determine whether the recalibration of each sensor negatively impacted the system's data quality. Data were collected from the system at each of the numbered locations with the RLMMS as well as with a handheld Minolta T-10 illuminance meter mounted on a tripod to the same height as the RLMMS sensors (approx. 78.5"). The pavement of each of the numbered areas was also marked for handheld measurements at the ground level following the departure of the vehicle from the location.

Results indicated a high similarity between data recorded through the use of the RLMMS and data recorded with a traditional handheld illuminance meter. Results of this evaluation are displayed below in Figure 12.

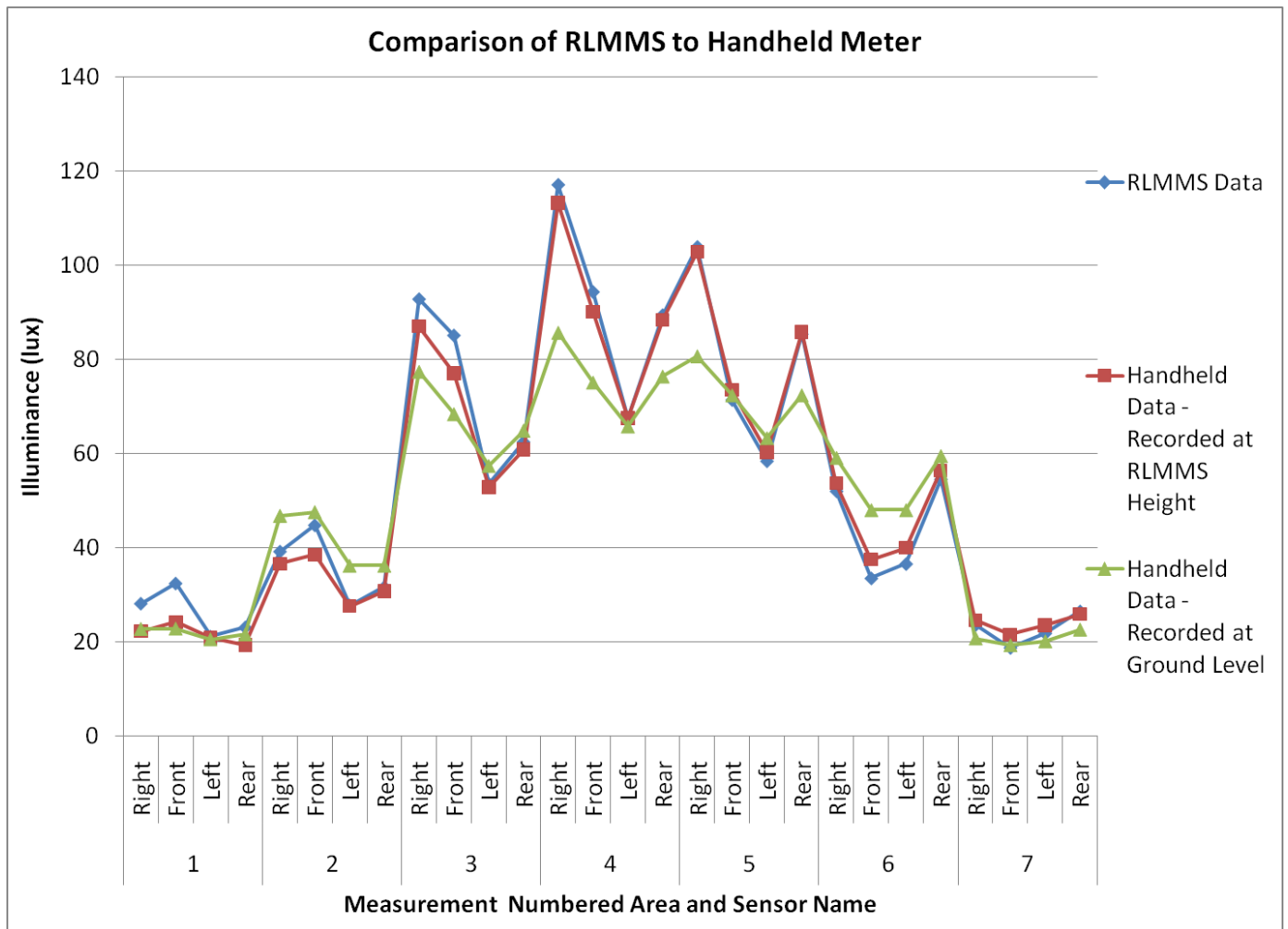


Figure 12. Graph. Comparison of RLMMS to handheld meter.

As can be expected, the light readings collected at the ground level tended to be less than that of the readings at the height of the RLMMS. Areas such as measurement areas #2 and #6 had ground level readings higher than those at RLMMS height. This may be due to the optics of the luminaire itself and the output being directed more toward the ground at these locations.

CHAPTER 6. SUMMARY AND CONCLUSIONS

The RLMMS system was developed by the Center for Infrastructure Based Safety Systems at VTTI in order to provide a tool to simultaneously measure multiple sources of visual information in the roadway environment. This system allows for continuous measurements of the lighting on roadways at highway speeds. It also allows for geographic information system evaluation of the lighting systems. This system allows for the measurement of lighting performance over a much larger area than hand measurement. (Update: as of July 2017, the system had measured over 5,000 miles of lighting.)

The R&R evaluation was found to be beneficial, as it confirmed that collection of data through the RLMMS may be repeatable and reproducible, as well as consistent with handheld measurements of illuminance. This system has already been shown to demonstrate high performance and has many applications in the assessment of roadway lighting conditions. Further additions and improvements to the system are being considered to further extend analysis of the roadway environment.

Future development includes the use of the spider on a robot system to measure sidewalks and parking areas. Additional sensors, such as temperature and road slope, may also be included in the system.

REFERENCE

1. Automotive Industry Action Group (AIAG). (2002). *Measurement systems analysis* (3rd ed.). Southfield, MI.