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16. Abstract

Transportation agencies routinely travel their extensive roadway networks conducting subjective roadway assessments of traffic control devices both day and night. Retroreflectivity is a good tool for product testing but can provide false positives for traffic control devices based on the approach geometry. This research project developed an objective nighttime assessment method for traffic devices that could be tied back to a form of level of service. The project also correlated luminance data with level of service. Researchers recommend the use the precise and approximate measurement methods in conjunction with nighttime inspections and retroreflectivity measurements to assess the accuracy and repeatability versus time.

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PROTOTYPE MOBILE LUMINANCE MEASUREMENT SYSTEM AND LEVEL OF SERVICE FOR EVALUATING RURAL HIGH-SPEED NIGHTTIME DELINEATION

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

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CHAPTER 1: INTRODUCTION

No matter how well a roadway system is designed for the intended traffic, that system is only as effective as the traffic control devices (TCDs) are at clearly delineating the drive path as it was intended in the original design. Those traffic control devices are also supplemented by signs for way-finding, warnings, and regulatory information. Using consistent color, shape, and placement of these various components helps ensure that these devices are visible to drivers so they can obtain the information they need to travel safely along simple to complex roadway networks throughout the day. However, once these devices are in place on a new or reconstructed roadway, transportation agencies must now assess when traffic control devices are no longer visible to drivers, and thus, no longer providing adequate guidance for drivers to safely navigate the roadway network.

Transportation agencies routinely travel their extensive roadway networks conducting subjective roadway assessments of traffic control devices both day and night (*1*). This method normally consists of a driver as the standard observer and a passenger recording the observations. This approach has proven effective in many instances, but with emerging technologies and new federal requirements regarding nighttime visibility (*2*), some states, such as Texas, have started investigating objective visibility assessment tools.

OBJECTIVE

This research project developed an objective nighttime assessment method for traffic devices that could be tied back to a form of level of service. While retroreflectivity is used in the federal requirements, it was decided to develop a prototype luminance-based measurement system to assess the nighttime visibility of TCDs. One of the benefits of measuring TCDs using luminance is that drivers assess the brightness of TCDs at night in terms of luminance and not retroreflectivity. Retroreflectivity is a good tool for product testing, but it can provide false positives for traffic control devices based on the approach geometry. For instance, a retroreflective sign may meet the minimum retroreflectivity requirements using a handheld retroreflectometer, but the fixed geometry of the handheld retroreflectometer does not account for sign twist. If a sign is twisted away from the road, a sign can be less visible to a driver than what the federal requirements meant to achieve, but handheld retroreflectivity measurements would not have captured this information.

The next objective of this research project was to correlate luminance data with level of service. In this objective, the research team collected human factors data and luminance data. The human factors data consisted of subjective visual assessments of roadway delineation under nighttime conditions that would be tied to the luminance data. These data would be used to develop a preliminary nighttime visibility inspection tool for TxDOT that would assess the level of service provided by in-situ TCDs along rural high-speed roadways in Texas.

CHAPTER 2: BACKGROUND

The researchers reviewed the pertinent literature with an emphasis on research and technological advances within the last 10 years. They open the discussion below on the technological advances in nighttime visibility measurement equipment, followed by recent research in the area of nighttime visibility, and level of service.

VISIBILITY MEASUREMENT TECHNOLOGY

Equipment designed to objectively quantify driving visibility has been developed with consideration for mobility, repeatability, and accuracy, among other things, but these devices have not always provided data that can be directly linked to human factors performance with respect to the impact of visibility. For instance, handheld pavement marking, marker, and sign retroreflectometers are some of the most common devices used to assess nighttime driver visibility. These devices are generally designed around fixed geometries that can be helpful in determining compliance with specifications, but can also limit the application of the data. While a handheld pavement marking retroreflectometer can measure the visibility of a pavement marking at 30 meters (~100 ft) in front of a driver, many of the nighttime driving environments might require a driver to see the roadway path beyond 30 meters. According to the *Green Book*, a typical driver needs approximately 150 meters (~300 ft) to come to a complete stop when traveling at 72 km/h (~45 mph) (*1*). Furthermore, for that specific type of device, the geometry is associated with a single light source placed directly over the pavement marking (*4*); which is not the intended driving condition.

Table 1 contains a list of four metrics that have been used with respect to measuring nighttime visibility. Retroreflectivity is probably used the most with respect to visibility, and from a department of transportation (DOT) perspective, will probably remain the most predominant measure when considering the minimum retroreflectivity requirements as stated in the *Manual on Uniform Traffic Control* Devices (MUTCD) (*2*). There are several handheld retroreflectometers that are on the market for state DOT use, but these have limited measurement geometries. There are some devices that can be used in the field and can provide additional geometries. However, retroreflectivity measurements that are made at various geometries are normally conducted in a laboratory environment and then modeled for real-world applications.

There are a few mobile retroreflectometers (*5,6,7*) that can be used to collect data at highway speeds, but practitioners must first ask if retroreflectivity is the best metric for evaluating nighttime visibility, especially when considering that the measured geometries may not directly evaluate what a driver needs. Figure 1 contains several different types of handheld and mobile retroreflectometer systems.

Table 1. Measurement Metrics Comparison.

Metric	Description	Comment
Retroreflectivity	Ratio of luminance return to a driver with respect to the illuminance falling on an object being viewed	Can be measured for specific geometries with repeatability, but the specific geometries may not assess the capabilities of a TCD with respect to when it needs to be visible.
Illuminance	The quantity of light falling on an object being viewed	Can be measured, can be directly linked to glare, but the measurements can be labor intensive and are sensitive to geometry.
Luminance	The perceived brightness of an object	Can be measured, can be used to assess glare, can be directly tied to visibility performance, and using new charged-coupled devices (CCD) photometer equipment, is not labor intensive to measure.
Visibility	An evaluation of a target object's luminance with respect to its surroundings and potential glare.	Is the most labor intensive, but is the only metric that combines luminance, glare, and background contrast into one value to assess visibility.

There are various illuminance meters that can be purchased on the market. Where retroreflectometers are exclusive to use on retroreflective products, illuminance meters are used in conducting photometric measurements in transportation visibility and other fields such as photography. Hence, they are less expensive and easier to purchase than retroreflectometers, and they are useful in urban areas or other areas that require overhead illumination.

Using uniform diffuse material, researchers and engineers can actually purchase equipment to measure luminance and back calculate illuminance. What makes luminance measurements even more useful is that luminance is tied specifically to the light return characteristics of the object being viewed. You can have the same illuminance in a location, but have two targets with different luminance values, which could impact a driver's ability to identify objects. For instance, if an animal has stopped behind a delineator post on the side of the road, a driver might only see the delineator as the luminance differences in the same region of interest might not allow the driver to see the low conspicuity animal behind the bright high conspicuity delineator post. This could be a problem if the animal advanced into the drive path.

a) Handheld Pavement Marking Retroreflectometer

b) Handheld Sign Retroreflectometer

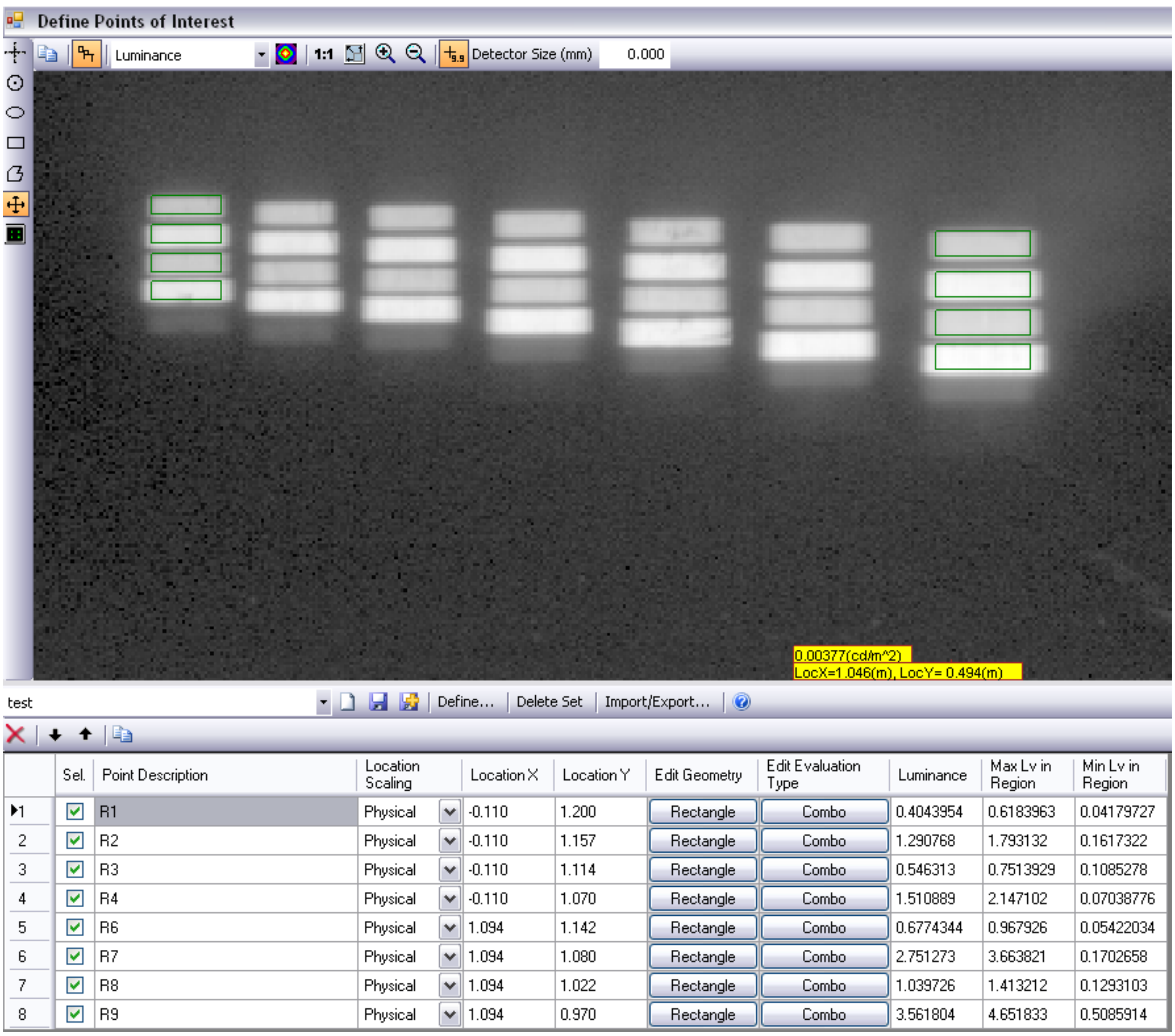
c) Mobile Pavement Marking Retroreflectometer

d) Mobile Sign Retroreflectometer

Figure 1. Retroreflectometers (*5,6,7*).

Another benefit of luminance measurements is in the area of technological advances that go into measuring luminance. The initial luminance meters were spot meters that measure the average luminance within a region of interest normally indicated by a dot that must be placed over the location to be measured. This can be problematic if the user needs to take measurements at multiple distances, and if the target to be measured is smaller than the measurement region. If the region of measure is smaller than the sample region at multiple distances and the region being measured is a different size, this can complicate how the 9measurements are compared.

Equipment that uses charged-coupled devices (CCDs) to measure luminance of the entire region being viewed on a pixel by pixel level has been developed that could be used to mitigate the problems associated with spot luminance meters (*8,9*). CCD technology coupled with the correct hardware and software now allows researchers and other users to take an image and process the luminance of specific items within the image, such as the individual retroreflective stripes on a traffic barrel (see Figure 2). These commercially available devices have a large dynamic luminance range, but what they currently lack is the ability to measure luminance under mobile conditions, such as at normal roadway speeds. This would be ideal for DOTs that want to evaluate the nighttime visibility of their roadways from the perspective of their driving population. However, mobile luminance measurements are still in the development stage and are primarily being collected in human factors visibility research studies.



	Sel.	Point Description	Location Scaling	Location X	Location Y	Edit Geometry	Edit Evaluation Type	Luminance	Max Lv in Region	Min Lv in Region
1	☑	R1	Physical	-0.110	1.200	Rectangle	Combo	0.4043954	0.6183963	0.04179727
2	☑	R2	Physical	-0.110	1.157	Rectangle	Combo	1.290768	1.793132	0.1617322
3	☑	R3	Physical	-0.110	1.114	Rectangle	Combo	0.546313	0.7513929	0.1085278
4	☑	R4	Physical	-0.110	1.070	Rectangle	Combo	1.510889	2.147102	0.07038776
5	☑	R6	Physical	1.094	1.142	Rectangle	Combo	0.6774344	0.967926	0.05422034
6	☑	R7	Physical	1.094	1.080	Rectangle	Combo	2.751273	3.663821	0.1702658
7	☑	R8	Physical	1.094	1.022	Rectangle	Combo	1.039726	1.413212	0.1293103
8	☑	R9	Physical	1.094	0.970	Rectangle	Combo	3.561804	4.651833	0.5085914

Figure 2. CCD Photometer Luminance Measurements.

VISIBILITY RESEARCH

Visibility research has been conducted in many ways over the years using a variety of metrics and human factors data. Two of the most common metrics are detection and legibility distance (*10,11,12,13,14,15*). These have been used as they are very intuitive to both practitioners and users, because an increase in detection/legibility distance directly relates to an increase in the amount of time available to drivers to respond to the information that the retroreflective traffic control devices provided. An increase in the amount of time available for a driver to react to the driving environment should correlate to an improvement in safety.

However, advances in retroreflectivity technology, such as the introduction of prismatic sign sheeting, introduced potential concerns with legend over-glow or glare (*10*) that are difficult to quantify. In the Carlson et al. study (*10*) evaluating the highway alphabet, the researchers investigated if the smaller stroke width and larger letter spacing that Clearview® offered provided improved legibility distance over the existing E-Modified highway alphabet. The use of Clearview® provided drivers approximately 0.68 seconds additional preview time at 70 mph.

Furthermore, the very nature of the sensitivity of the human eye makes it more difficult to see relatively small differences between materials as the performance of retroreflective products increases. Since the human eye responds to light on a logarithmic scale, larger increases in light intensity are required for a person to perceive a difference (*16*). In other words, brighter materials require larger differences between them before drivers will see a benefit. This also goes for smaller differences having a greater impact at lower lighting levels. This is where minimum retroreflectivity or luminance levels make a difference. That said, those minimum levels might need to take into context brighter competing objects in the nighttime driving environment.

In a joint effort, the Virginia Tech Transportation Institute and the Texas Transportation Institute completed research in 2011 that was designed to investigate the impact of a variety of different static, dynamic, low visibility, and high visibility objects in the nighttime driving environment (*18*). The researchers used the standard metrics (i.e., legibility and detection distance) and other metrics (glance duration from eye-tracking, and lateral position) to evaluate the impact of varying object visibility levels of signs, pavement markings, and other non-TCD devices (i.e., standard visibility target, bucket, deer decoy, pedestrians, cyclists, parked car).

While there are many interesting findings from the research, the most applicable one to this research is the application of collecting mobile luminance.

Currently, there are no commercially available mobile luminance systems. However, the technology is under development and shows promise in a number of applications. While these researchers (*18*) used the system to measure the luminance of a variety of targets for human factors evaluation, the same system could be adapted as a tool for DOTs to evaluate the nighttime visibility of their roadway assets.

Carlson et al. conducted visibility research to assess the nighttime visibility of various roadway delineation TCDs using CCD photometry (*19*). The research team gathered data from a static condition with a CCD photometer, and then analyzed the data using techniques that were based on a Visibility Level (VL) (*20*) model that had been used in previous research to assess visibility associated with roadway lighting (*21*), pedestrians (*22*), and pavement markings (*23*). What this suggests is that one potential method to assess the level of service of TCDs would be to use data from mobile luminance data collection technology and VL.

LEVEL OF SERVICE

In transportation, level of service (LOS) is defined in the *Highway Capacity Manual* (HCM) by the designations A (best) through F (worst) for a transportation facility, such as a multi-lane highway (*24*). LOS is an effective means for communicating with public officials, highway users, and other stakeholders about asset performance and resources needed to ensure adequate performance. Each facility is able to have LOS defined in terms of a specific measure of effectiveness.

While the HCM provides guidance on establishing the LOS associated with transportation facility throughput, more recently transportation agencies have shown interest in applying LOS to other transportation-related assets such as traffic control devices (*25,26*). Both of these documents start the discussion on LOS with respect to TCDs, but their current recommendations focus on the presence of a particular TCD. This method may need revision for at least the following reasons:

- This is not tied to safety or at least some safety-related metric, and it would reward the minimalist approach to installing TCDs.

- The presence of a TCD, such as a pavement marking or sign, does not guarantee a benefit to the driving public if it does not provide adequate contrast to ensure that a driver has seen the device.
    - Practitioners have started installing contrast pavement markings in place of standard white pavement markings on Portland concrete to provide sufficient daytime contrast.
    - The *MUTCD* now requires states to put maintenance policies in place that help ensure their roadway signs are above a certain level of retroreflectivity (*2*).

Potential Considerations for Selecting Performance Measures

In *NCHRP 551*, several different categories of asset management performance measures were listed that warrant consideration when trying to devise the appropriate performance measures for use in calculating LOS. These include preservation, accessibility, mobility, operations and maintenance, safety, environmental impacts, economic development, social impacts, security, and delivery (*25*). While intuitiveness is not listed, the report also emphasized that the measures should be intuitive to the practitioners and their public users. With respect to TCDs, preservation, mobility, operations and maintenance, environmental impact, and safety could all be areas of consideration when trying to develop the appropriate performance measures. However, safety and preservation are probably the two most likely candidates.

Safety

As a disproportionate number of crashes with respect to travel volume occur at night, it can be suggested that visibility limitations associated with nighttime driving is an area of concern for DOTs. Safety studies are a direct measure of how a particular roadway improvement, such as adding a flashing beacon to a stop sign, would impact the driving environment. While safety studies could be a component in an LOS asset management system, safety studies require several years of data and large data sets for evaluation. Furthermore, as several years of data are compiled, there is no guarantee that other roadway improvements or changes in the traffic flow characteristics did not impact the results. Surrogate safety measures have also been used to gather traffic observational data to assess safety improvements associated with different traffic control devices using shorter intervals.

However, safety may not be the most efficient performance measure with respect to TCDs for at least two reasons. As mentioned previously, the primary drawback is time and the associated potential for additional changes in the driving environment over the period of the study. What makes more sense would be to continue to use safety studies in a limited measure through strategic research initiatives that focus on detailed evaluations on different TCD treatments for improving roadway safety. Following this thought, it would be more efficient to focus on preservation of the existing TCDs as they are implemented to improve safety.

Preservation

As the current *MUTCD* already requires the maintaining of minimum retroreflectivity for signs (*2*), it would be logical to use retroreflectivity as a metric for evaluating retroreflective TCDs. However, Carlson et al. have already shown VL to be better tool than retroreflectivity for assessing visibility of pavement markings and markers (*19*). The researchers evaluated lines at the suggested minimum pavement marking retroreflectivity, and then calculated the corresponding VL values for comparison with the VL values that existing pavement markings and markers in Alaska provided. They showed that overhead illumination can provide as good, if not better, VL values for pavement markings that are below the suggested minimum pavement marking retroreflectivity values.

What VL currently lacks is an efficient evaluation methodology that is automated, so another potential consideration is the use of expert nighttime observers. While this is subjective, it has been shown to be an effective means to evaluate sign sheeting performance (*27*) and pavement marking performance (*28*) with respect to end-of-life evaluations. One suggestion could be to provide both options to practitioners for their evaluation purposes. For instance, nighttime inspections by experts could be conducted on a large scale with supplemental work completed using VL for more complex driving environments or regions that have experienced problems from crashes and/or driver complaints.

The proposed LOS template for TCDs as described in *NCHRP 667* (*26*) was replicated in Table 2 and modified to include other potential metrics and expanded the asset elements. The primary changes were the expansion of the asset elements, the addition of a visibility component to the indicator, and the addition of the quantitative evaluation of measure focused around visibility level.

Table 2. Revised LOS Traffic Control Devices (*26*).

Asset Class	Asset Elements	Definition	Indicator	Measure
Traffic Control & Management Devices (Passive)	Regulatory Signs	Speed limits signs and other black legend on white background signs, and stop signs and other white legend on red background signs that are designed to provide regulatory guidance.	% deficient with respect to signs that do not provide sufficient nighttime visibility or physically missing signs.	Evaluated using trained nighttime observers, or use luminance contrast rating with respect to visibility level.
	Warning Signs	Black legend on yellow background signs designed to alert drivers approaching a roadway feature, such as a horizontal curve, that may require additional attention when driving through it.	% deficient with respect to signs that do not provide sufficient nighttime visibility or physically missing signs.	Evaluated using trained nighttime observers, or use luminance contrast rating with respect to visibility level.
	Guide Signs	White legend on green background signs that provide destination and routing information.	% deficient with respect to signs that do not provide sufficient nighttime visibility or physically missing signs.	Evaluated using trained nighttime observers, or use luminance contrast rating with respect to visibility level.
	Pavement Markings/Markers: • Edge lines • Lane lines • Centerlines • Rumble stripes • Reflectorized Raised Pavement Markers (RRPMs • Delineators	All continuous, discontinuous with repeat spacing, or single treatment pavement marking/marker installations designed to provide lane keeping guidance.	% deficient with respect to a cumulative rating based on the entire delineation system with respect to daytime and nighttime contrast for given roadway segments.	Evaluated using trained nighttime observers, or use luminance contrast rating with respect to visibility level.
	Special Pavement Markings • Stop bars • Crosswalks • Traffic calming • Horizontal signs	Single treatment pavement marking installations designed to provide additional routing guidance or safety for roadway users and adjacent facility stakeholders, such as pedestrians.	% deficient with respect daytime and nighttime contrast and content for horizontal signs for required treatments (this would avoid penalizing agencies for going above the requirements).	Evaluated using trained nighttime observers, or use luminance contrast rating with respect to visibility level.
	Roadside Safety Hardware: • Crash attenuators • Guardrails • Rumble strips • Animal fencing	Devices used to increase safety through either early passive alert, such as audible and vibratory warnings from rumble strips, or through physically redirection or rapid deceleration of errant vehicles.	% non-functional based on an accepted percentage.	% damaged with respect to length with weighting for key features, such as end treatments
	Work Zones	All black legend on orange background signs that alert drivers to the approach to a construction work, and any other devices such as temporary pavement markings and beacons.	Missing, non-reflective, or misaligned TCDs.	Evaluated using trained nighttime observers, or use luminance contrast rating with respect to visibility level.
	School Zones	All TCD devices associated with a school zone, which could include signs, crosswalks, and flashing beacons.	Missing, non-reflective, or misaligned TCDs.	Evaluated using trained nighttime observers, or use luminance contrast rating with respect to visibility level.

Table 2. Revised LOS Traffic Control Devices (*26*). (Continued)

Asset Class	Asset Elements	Definition	Indicator	Measure
Traffic Control & Management Devices (Active)	Traffic Signals	All fully actuated traffic signals to single flashing stop or yield warning beacons.	Missing, damaged, or misaligned.	% elements deficient
	Beacon Alert Systems	Specialized active warning systems used to alert drivers to special conditions such as weather warnings and contra-flow.	Missing, damaged, or misaligned.	% elements deficient
	Dynamic Message Signs (DMS)	Electronic signs designed to provide DOTs a means to communicate travel time and other information throughout the day.	Missing, damaged, or misaligned.	% elements deficient

CHAPTER 3: PROTOTYPE MOBILE LUMINANCE MEASUREMENT SYSTEM DEVELOPMENT

In this chapter, the researchers discuss what steps they took to develop the prototype mobile luminance measurement system and concluded with the detailed specification. Below are the objectives for the system as defined by the project panel and researchers that were used throughout the prototype development phase of this project:

- Develop a luminance-based mobile data collection system for assessing the nighttime visibility of traffic control devices, such as pavement markings and signs.
- The system should have geo-coding capabilities for documentation purposes.
- The system should be mobile from one vehicle to another.
- The system should be modular to allow for upgrades and repairs.
- The system should use National Instruments LabVIEW™ software in the core programming. All coding should be well documented to allow for easy troubleshooting and modification by TxDOT staff.

DEVELOPMENT PROCESS

There were several different options for collecting luminance data from handheld spot luminance photometers to true 16-bit CCD image photometers that could be used. However, at the time of this project, no one company had a system that could measure luminance of individual TCDs at highway speeds. Subsequently, the researchers built on their experience with their existing mobile luminance system and improved upon it. The heart of any photometric measurement system is the quality and capability of the photometer(s) used in its development.

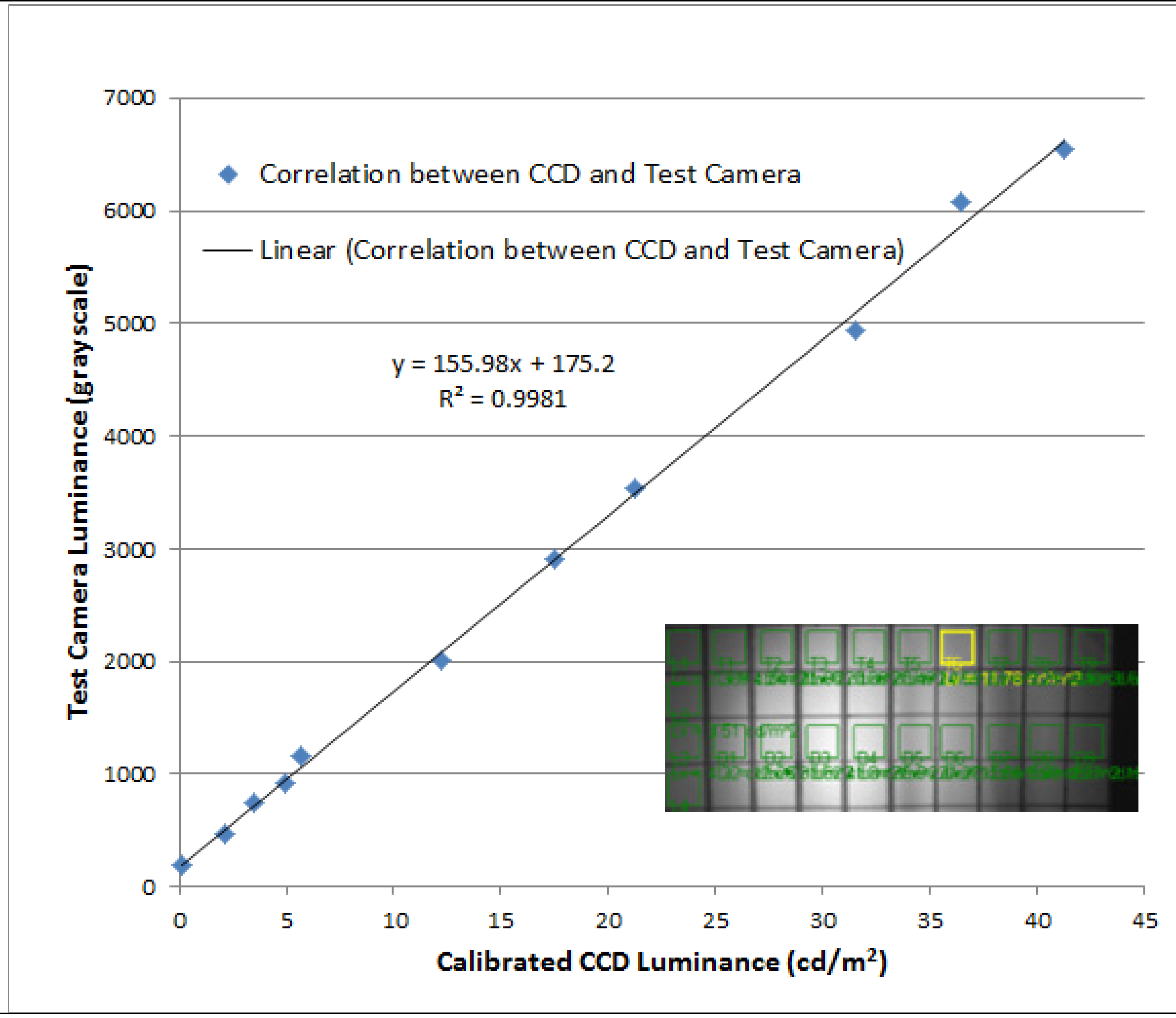
Camera Testing

The researchers tested several different styles of cameras to be used as photometers in the mobile luminance measurement system (see Table 3). Each camera was tested with regard to ease of use and the output of the images. Ease of use was a subjective rating and there appeared to be little difference with respect to ease of use for each camera with one primary exception: communications. Cables for Firewire IEEE-1394b are stiffer and more expensive to use than Ethernet-capable cameras. Stiffer cables will make installation more difficult, and there is no reason to pay more money for higher levels of installation difficulty, especially when data transmission is not diminished. The only advantage to Firewire appeared to be that the cameras could be powered through the cable, while the Ethernet cameras required a separate power cord. This was not found to be a problem with installation when compared to greater cord flexibility with Ethernet connections. In addition, new cameras are now available with power over the Ethernet (PoE) capabilities that would allow for a single cord to go to the cameras similar to their Firewire counterparts. Special capabilities, such as controlling lenses and special triggering options, were not evaluated within this study.

Table 3. Cameras Tested.

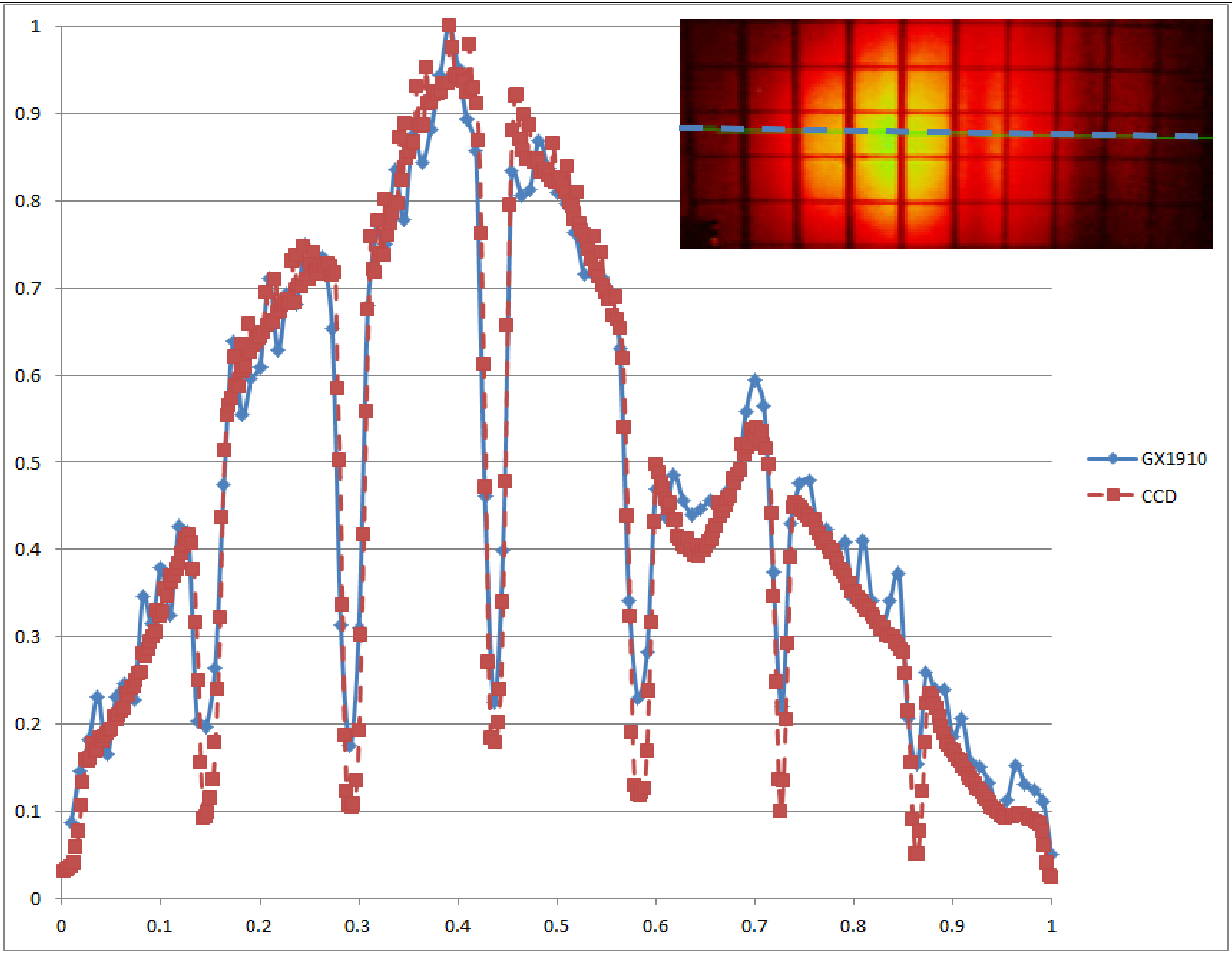
Make/Model	Chip	Resolution (pixel × pixel)	Pixel Size (μm)
PointGrey/GRAS20S4C-M	Sony ICX285 2/3" CCD, Mono, 30 fps	1624 × 1224	4.4
AVT/ Prosilica GX1910	Kodak KAI-02150 2/3" CCD, Mono, 55 fps	1920 × 1080	5.5
Basler/A102f	Sony ICX285 2/3" CCD, Mono, 15 fps	1392 × 1040	6.45
Basler/piA1600-35gm	Kodak KAI-2020 CCD 1/2", Mono, 35 fps	1608 × 1208	7.4
Basler/scA1400-17gm	Sony ICX285 2/3" CCD, Mono, 17 fps	1392 × 1040	6.45

With each camera, the researchers took a myriad of images of a white diffuse surface. The initial testing was done with a simple white cloth fabric that had been marked with a grid system so that the images could be correctly scaled and compared as the cameras differed in their pixel resolution and pixel size (see Figure 3). The cloth surface was better than 90 percent diffuse reflective and considered appropriate for the comparison evaluation. Figure 3a shows the illuminated grid and the associated correlation between the calibrated CCD images and a test camera. The grid was not uniformly illuminated to assess whether the relationship between the measurements from the two devices was linear or not over a range of illuminance levels for a given set of measurements. Figure 3b shows a graph of the dotted line in the image that crosses the illuminated grid. The image looks different than the image in Figure 3a because a software-based visualization filter was applied to make it easier for the researchers to view the grid system. This filter did not alter the data. The graph in Figure 3b shows good correlation, but the uncalibrated camera does appear to overpredict the luminance versus the calibrated CCD.



a) Mean Luminance Grid Comparison

Figure 3. Camera Comparison Grid Method.



b) Single Line Profile Grid Comparison (Normalized Data)

Figure 3. Camera Comparison Grid Method (Continued).

These images were taken at different gain, shutter speed, and ambient lighting conditions to assess the luminance range associated with each camera under varying camera settings. Each of these camera images resulted in a grayscale image that was then post-processed and compared to images taken with the PM-1600 CCD Photometer, a 16-bit camera calibrated to measure luminance. During preliminary testing, the researchers found that setting the gain to 300 provided the best overall images over the given shutter speed range from 5 ms to 100 ms.

The range of 5 ms to 100 ms range was selected for two reasons following below. This range was shown to provide ample ability to measure the dimmest to the brightest retroreflective TCDs expected to be measured on the road. The goal was to be able to measure from 0.1 to 100 cd/m^2.

- The researchers selected this range based on field experience. TCDs that meet the minimum retroreflectivity requirements would not pass below 0.1 and would exceed the minimum above 100.
- The second reason dealt with the limitations of the camera and the driving condition. The camera could not have an exposure below 5 ms, so if a TCD was too bright for that condition, the researchers would need to apply neutral density (ND) filters. On the other end with 100 ms, it was believed that beyond 100 ms the images be too blurred to provide usable ones for analysis. To give a little perspective, data collected at 60 mph at 100 ms would result in an image exposed while traveling 8.8 ft. The relationship of luminance to grayscale for a given set of conditions was found to be scalar, and so the researchers developed scalar conversion values for each of the cameras under a given set of conditions.

Filter Testing

When creating a photodetector, it is critical to make sure that the spectral responsivity of the detector is known and corrected to weight the incoming light as it would be seen by the system that the photodetector is trying to emulate, such as the human eye.

There are a few ways to adjust a photodetector to compensate for the sensitivity of the human eye.

- One would be to adjust the design of the imaging chip used to collect the data. While this can be done, it may not always be the most practical for designers. For instance, creating a single chip for multiple applications is cheaper in mass production than to have several different imaging chips.
- Another option would be to filter the incoming light with a filter color wheel to ensure the chip is only measuring specific wavelengths of light; the values can then be weighted to match the spectral response that is needed. However, this would not work for a mobile application. This situation then leads to the idea to use multiple cameras and take simultaneous images with color filters to create the same result as the color wheel. This would work for a mobile condition, but the requirement for multiple cameras would make installation difficult, expensive, and add the requirement to trigger the cameras to ensure the timing of the images.

- One of the last options, and the one that the researchers used in this project, would be to install a filter matched to the spectral responsivity of the chip and the observer that the photodetector was trying to emulate. In this case, the human eye's spectral responsivity is said to follow the V lambda curve, as shown in Figure 4a.

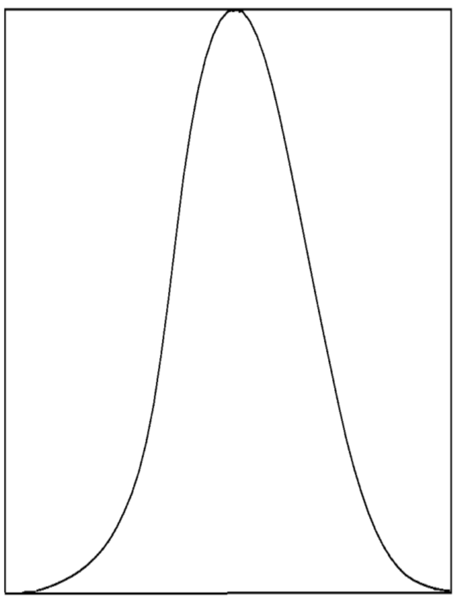
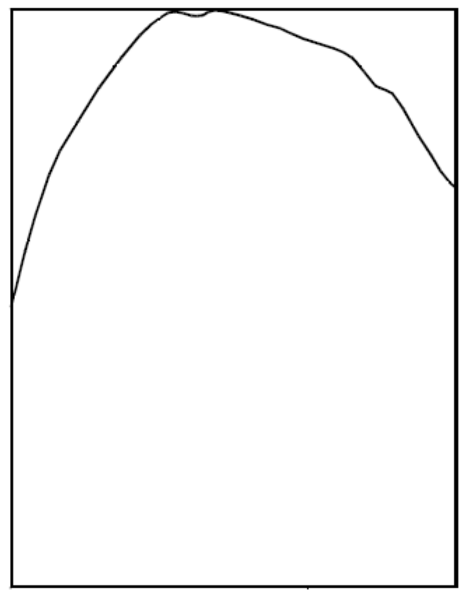
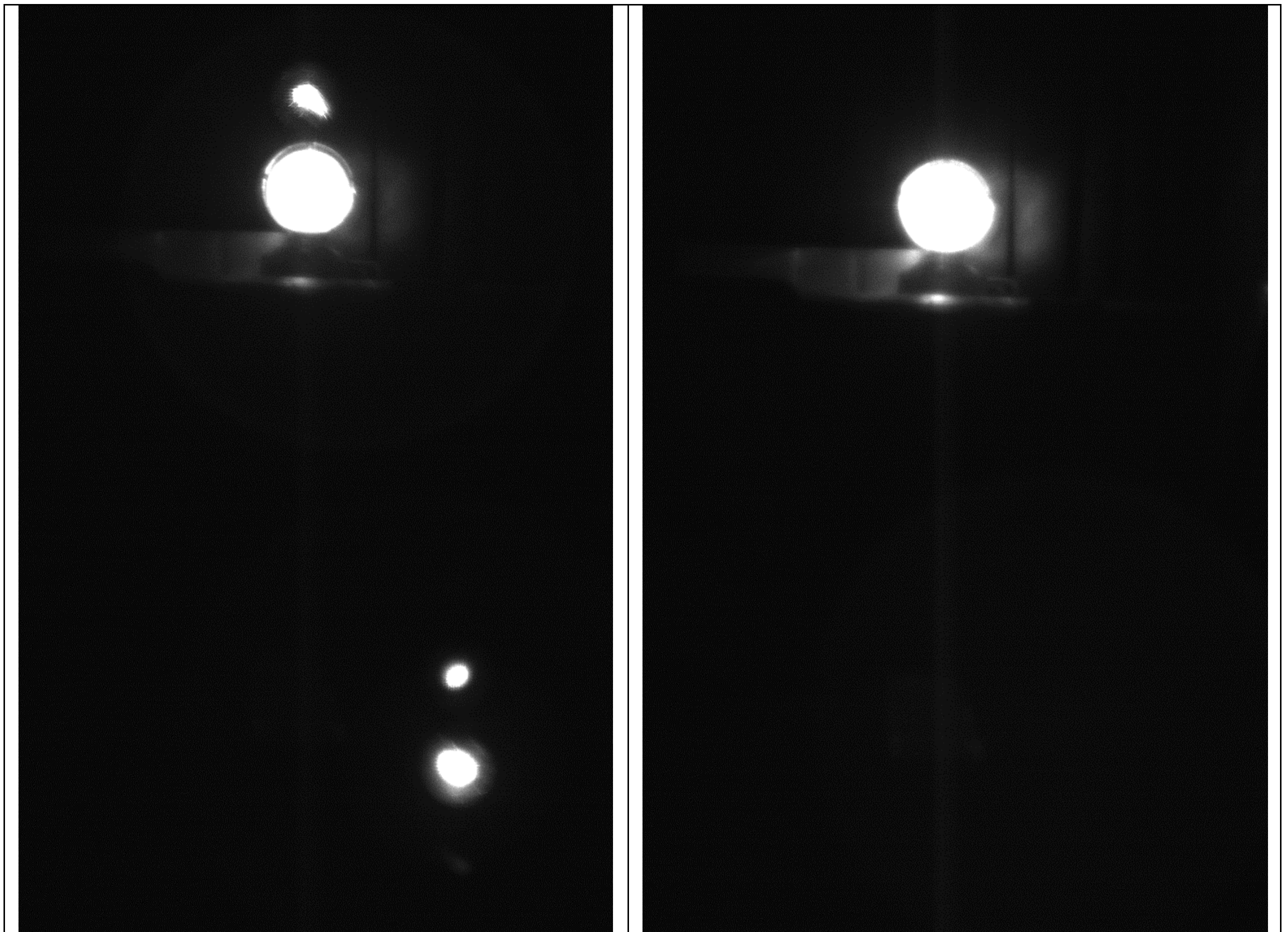
	
a) 1931 CIE Human Photopic (Wikipedia)	b) Basler scA1400-17gm (Manual)

Figure 4. 400–700 nm Luminous Efficiency Function Comparison.

Figure 4 also shows the spectral responsivity of the camera selected for the development of the prototype. What these two graphs show is that without a V lambda curve adjustment, the camera would report higher luminance values for the red and blue wavelengths than a human observer would experience.

In the process of testing the cameras with a V lambda filter, the researchers discovered at least two potential issues, reflection and halation. Distortion in the form of reflection occurred when the filter was placed in front of the focusing lens. Internal reflection between the face of the lens and the filter can generate false secondary images. This became evident when imaging nighttime scenes with roadway lighting. Figure 5a shows the secondary false images above and below a test beacon. Figure 5b confirms the occurrence of internal reflection.

The researchers then looked at other possible ways to install the filter. The manufacturer of the filter suggested mounting the filter at slant to the incoming light, such as a 3-degree offset, but this did not remove the problem for bright objects, such as lights. The researchers then moved the filter between the focusing lens and the imaging chip, which is set at the focal plane. The researchers discovered halation to be a problem with an internal filter, but the halation decreased as the filter was moved closer to the focal plane. Upon further investigation of some of the methods that camera manufacturers used to generate color images, it was found that one method actually was in the form of placing filtering lenses over individual pixels and is referred to as a Bayer filter (Basler manual).



a) External Filter	b) No Filter

Figure 5. Internal Reflection Problem with External Filter Installation.

Calibration

A photodetector is only as accurate as its calibration, so the researchers used a calibrated PM-1600 CCD Photometer to conduct calibration measurements for the prototype cameras. Again, the researchers used an illuminated white diffuse cloth surface to calibrate the cameras. The grid network on the illuminated white diffuse surface allowed for the images to be properly scaled. Again, the gain was kept constant, as well as other settings, and only the exposure and illumination levels were adjusted. The gain value used was selected based on a myriad of tests conducted to evaluate the relationship of gain, exposure, lens, and; the final value selected was 300. An example of the conversion factor estimate equation for a range of exposures for one lens at one particular f-stop is shown in Figure 6 for two different, but identical cameras. The cameras did not appear to require different conversion factors. The researchers then tested the potential difference between lenses with different focal lengths and did not find one, as shown in Figure 7. F-stop and exposure were the primary contributing factors on selecting appropriate conversion factors from grayscale luminance to V lambda corrected luminance in cd/m^2. Table 4 shows the final conversion factor formulas for a given range of f-stops and exposures.

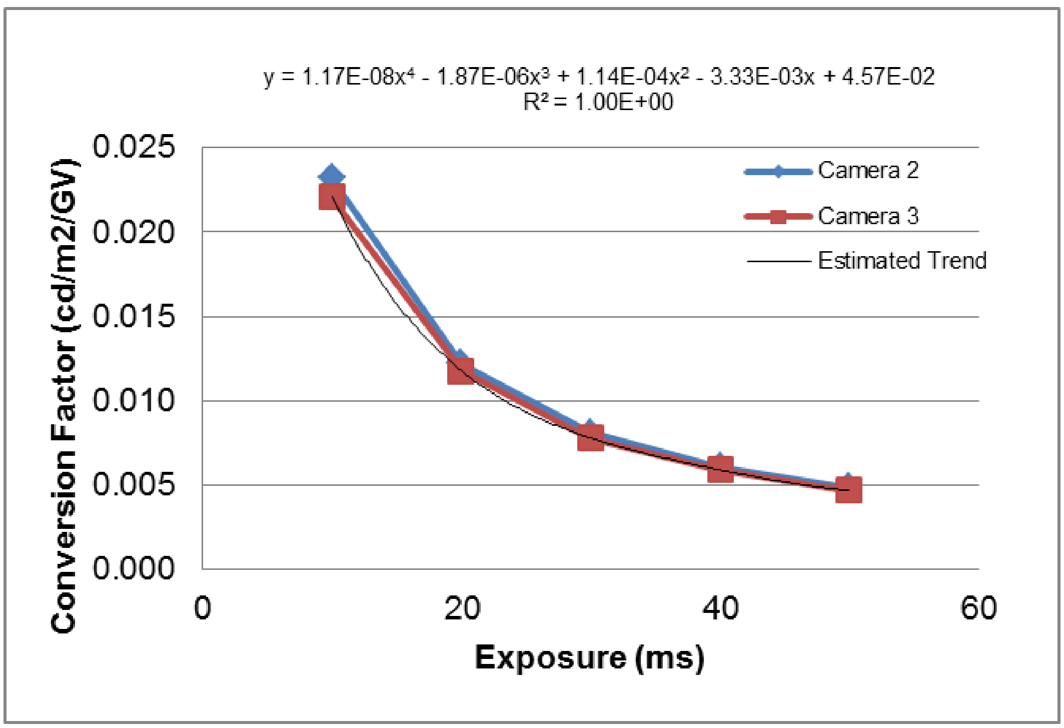


Figure 6. Camera Comparison.

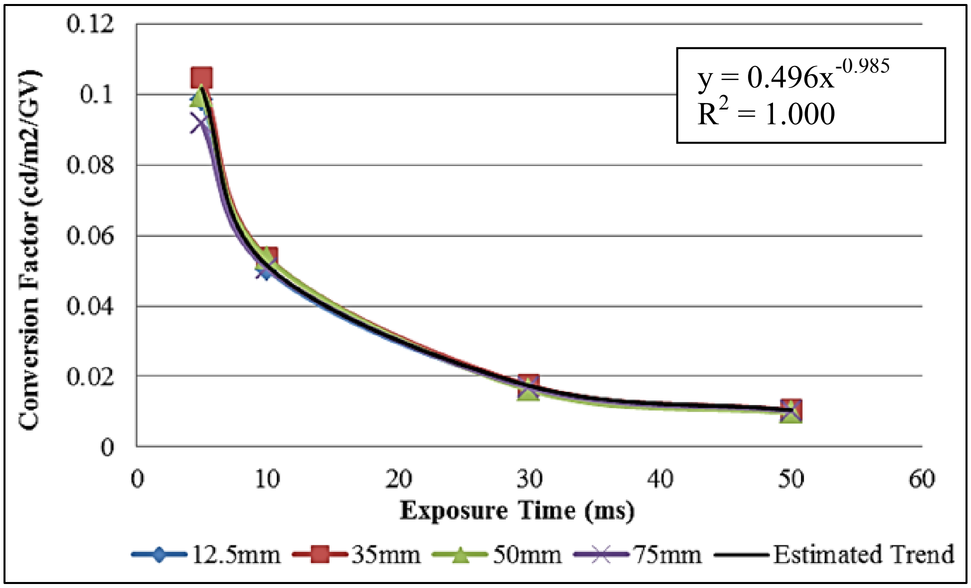


Figure 7. Focal Length Comparison.

Table 4. Grayscale-to-Luminance Conversion Factors.

Lens[a]		Camera[b] Exposure (ms)	Luminance[c]		
F-Stop	**Focus**		**Min**	**Max**	**Formula**
2.8	∞	5	5	400	$y = 0.496x^{-0.985}$
		10	1	200	
		50	0	40	
8	∞	5	50	2,500	$y = 2.5574x^{-0.887}$
		10	20	1,300	
		50	5	300	
22	∞	5	150	10,000	$y = 7.5837x^{-0.661}$
		10	100	6,700	
		50	50	2,300	

[a]All lenses were Fujinon, 1.5-megapixel, 1-inch diameter lenses. The V lambda filter was placed between the lens and the camera CCD imaging chip.
[b]The exposure time is based in milliseconds (ms) and uses an electronic shutter whereby the camera only reads the collective energy within a pixel over the preset duration. The gain is fixed at 300 and is below the midpoint of the available range, so it is low in comparison to the maximum available value. This particular value was chosen based on empirical laboratory testing whereby the system showed the most consistent performance regardless of lens type or setting or camera exposure.
[c]The minimum (min) and maximum (max) values describe the recommended dynamic range available for measurement. If the user believes that the luminance values he/she would like to measure would exceed the range, the user should select more appropriate settings. The factor is the value that should be used to convert the grayscale image values into luminance. This is the value that should be input in the mobile luminance data collection software if it is not already preset.

Interface Development

The interface development was designed around the original project objectives to provide TxDOT with a mobile field luminance measurement system for TCDs providing nighttime delineation. This process was iterative and combined with the field testing, human factors data collection, and demonstrations with TxDOT over the course of the project. The researchers do not discuss this process in detail here but throughout the remaining sections of this report; however, the researchers detail below the general concepts that went into the interface development:

- A way to take single or continuous images using a calibrated camera.
- A way to calibrate the camera and make adjustments to the calibration.
- A way to geocode the images and tag the images with failure and other information.
- A way to assess the in-field luminance of TCDs and post-process those images.

Field Testing

The prototype system was tested in the field numerous times for various different purposes throughout the duration of the project. The early testing focused on the equipment operation from recording images and conducting in-field image processing. Later as the interface developed and the calibration testing was revised, the researchers tested the luminance values returned in the field using the newly calibrated mobile field luminance cameras.

The researchers selected roadway segments that allowed for static measurements with their calibrated PM-1600 CCD photometer. They took static images with the calibrated PM-1600 CCD photometer and their newly calibrated mobile field luminance cameras. They then took identical images while driving. These images were compared first across the static images, which confirmed that the laboratory calibration held for the in-field measurements in a static condition. The images were compared between the static and mobile. There was no way to guarantee that the images were taken at the exact same point as the static images, but the numbers were compared and believed to be accurate for the intended use of TxDOT.

The researchers also investigated the differences in lenses. Larger focal length lenses provide greater magnification of the forward scene, which improves the signal of small objects in the distance. This is particularly beneficial when trying to measure individual letters of a positive contrast sign. It was found that a 35 mm lens was the minimum that should be used when trying to measure a positive contrast sign, and a 75 mm was preferred. This created a slight problem since the 75 mm lens made it more difficult to aim a single camera to capture all positive contrast signs. The researchers noted this issue and moved forward. One possible work-around for this issue would be to use a camera with a higher pixel density and similar or large chip size, but there is the possible decrease in light sensitivity if the pixel size was decreased as the pixel density increased. A 12.5 mm lens was also evaluated and found to give a wide field of view, but the pixel resolution was of concern for TCDs that need to be viewed from distances beyond 100 ft (30 m). At that distance, a single pixel would measure an area approximately 0.75 × 0.75 inches.

PROTOTYPE SPECIFICATION

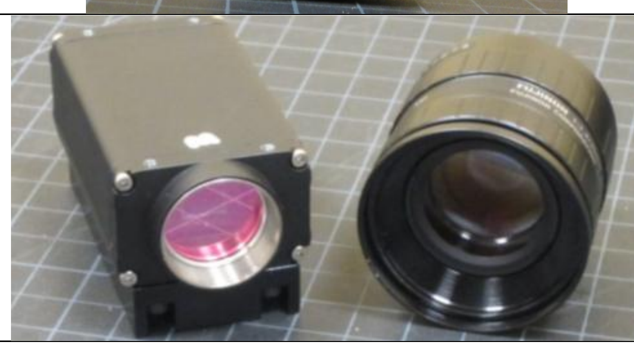
Based on the experience of the research team and the testing described above, the researchers purchased the components and software necessary to make a two camera luminance-based mobile system. As there was not a commercially available turnkey system to purchase, the research team made the purchase based on the initial specification below. Following the specification, the research team has started generating a list of optional equipment that TxDOT may want to consider for future systems that would give additional functionality beyond the scope of this project.

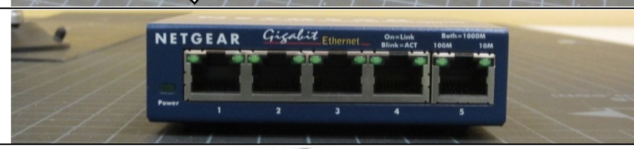
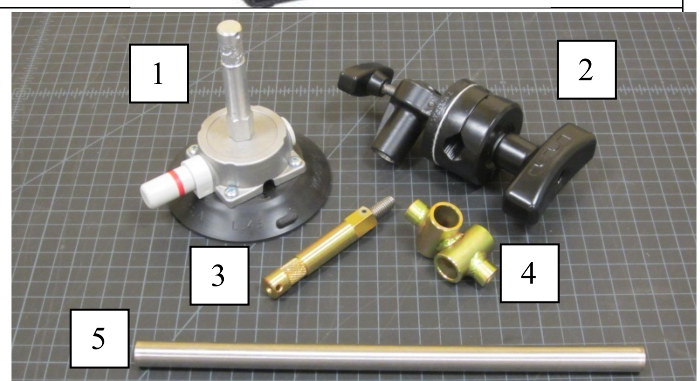
- 2 – Basler Scout cameras (scA1400-17gm) (*1*).
- 2 – 75 mm megapixel fixed focal length lenses.
- 2 – Photopic filters.
- 2 – Camera power supplies.
- 2 – Gigabit Ethernet cables.
- 1 – Computer.
    - 2 GHz Dual Core or faster/better processor.
    - 4 GB DDR3 1300 MHz RAM or more/faster.
    - 500 GB 7200 rpm hard drive or larger/faster.
    - 2 to 4 – Gigabit Ethernet ports.
    - 4 – USB 2.0 or more/faster ports.

    - 1 – RS232 port.
    - 1 or more additional PCI-express ports available for future upgrades.
    - 1 – DVI port.
    - Built-in or separate 15-inch LCD monitor or better.
- GPS.
    - 5 Hz or higher sample rate.
    - 3 meter accuracy or better.
- Optional equipment.
    - 3-D LIDAR – the use of 3-dimensional LIDAR sensors has been used in many surveying applications and could be adapted to provide accurate locations for roadside hardware from a mobile data collection platform. This could be beneficial when trying to develop detailed asset log files for use in asset management databases and for implementing LOS calculations for TCDs along the entire TxDOT highway system.
    - Remote trigger – different types of remote triggers could be added to the system to either add other logging features and/or to initiate, stop, and code the luminance imaging process.
    - Microphone – a microphone system could be added to store audio notes from data collection activities.

The actual system components purchased are shown in Table 5.

Table 5. System Specifications.

Computer	
Dell Latitude E6520 Laptop 2.5 GHz i5-2520M 4 GB DDR3-1333 MHz RAM 256 GB Solid State Drive Gigabit Ethernet Port USB 2.0 Port (4) e-SATA Port Bluetooth Wireless Wireless LAN [802.11a/b/g/n]	
Software	
Microsoft® Windows® 7 (64-bit) Microsoft® Office 2010 National Instruments LabVIEW™ TTI Luminance Data Collection Software TTI Data Reduction Software	
Qstarz 818XT 10 Hz GPS Receiver	
Camera	
Basler Scout Sca1400-17gm with Internal V lambda Filter	

Fujinon 1″ 1.5 Megapixel Lenses (4) 1. 12.5 mm [CF12.5HA-1] 2. 35 mm [CF35HA-1] 3. 50 mm [CF50HA-1] 4. 75 mm [CF75HA-1]	
Ethernet Switch	
PowerLine Inverter 12VDC/120VAC 200W	
Suction Cup Camera Mount 1. 4.5" Suction/Vacuum Cup with 3/8-16 Spud 2. 2-1/2" Hollywood Grip Head by Matthews Studio Equipment 3. 5/8" Baby Spud with 3/8-16 Female Thread at Base and Allen Key Set Screw Stainless 1" x 3/8-16 4. Baby 5/8" Cross 5. Redrock 12" 15 mm Stainless Rods	
Bogen Manfrotto Mini Ball Head 494	

CHAPTER 4:
HUMAN FACTORS STUDY

In this chapter, the researchers discuss the human factors study conducted to help develop the LOS for assessing the effectiveness of TCDs under nighttime conditions along high-speed rural roadways. The study design is discussed first and followed by the analysis of the impact of different TCDs and their varying levels of nighttime luminance on predicting driver satisfaction. These findings will then be applied to the discussion of LOS in Chapter 5.

STUDY DESIGN

Subjective and objective data were collected in an experimental human factors study. Participants were instructed to drive a closed-course and an open-road course while providing the researchers with their subjective assessment of various TCDs regarding the ability of the TCDs to provide positive nighttime guidance along the study route. Luminance data were also collected.

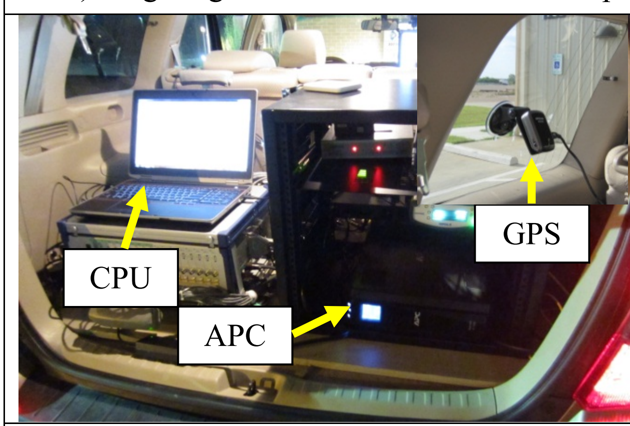
Equipment

The primary piece of data collection equipment was the prototype mobile luminance data collection system. The luminance images and subjective responses were geocoded, so the data could be merged. While the system can use two cameras, only one camera was required for the human factors nighttime study. It was placed at the height of the center of the driver headrest, but just to the right of the rear view mirror as shown in Figure 8a. This would provide a similar observation angle as the driver without occluding the driver's forward view of the roadway.

The researchers installed a different set of headlamps that could be controlled to simulate lower performing TCDs along the closed course. Using the controller depicted in Figure 8b, the researchers could fine-tune the lighting output and lock the controls, then use a set of switches to change between settings both quickly and with repeatability. The researchers tuned the headlights by turning the newly installed sealed-beam halogen bulbs to 100 percent output and adding supplemental light with vertical optically aligned (VOA) projection style HB4 halogen headlights. There were two pairs of VOA headlights placed below the rectangular sealed-beam headlights. These VOA headlights increased the near-field light in front of the study vehicle (approximately 50 ft out from the center of the headlight). One set of VOA headlamps were used when the sealed beam headlamps were at 100 percent output. Then, the sealed beam headlamps were reduced below 100 percent output to a level that cut the far-field light in front of the study vehicle (approximately 100 ft out from the center of the headlight) to approximately half of the original. This also reduced the near-field light, so the secondary VOA headlamps were tuned to a level that brought the near-field light back to previous setting where the sealed-beam headlamps were at 100 percent output. As the VOA headlamps did project some light into the far field, this was an iterative process to find the final settings. All of the adjustments were verified with a T-10 Minolta illuminance meter. The near-field illuminance levels were set based off the original near-field illuminance levels produced by the original equipment manufacturer (OEM) headlamps on the 2004 Toyota Highlander.

a) Lighting and Luminance Camera Setup

b) Headlight Controller



c) Computer, Power, and GPS

d) Data Collector Station

Figure 8. Human Factors Data Collection Setup.

Route

The study route consisted of closed-course and open-road study segments. Participants drove a portion of the closed course first, then the open road. After completing the open road section, they returned to the closed course for a few additional laps through the closed course before completing the study.

Closed Course

The closed-course evaluation was conducted at the Texas A&M University Riverside Campus and consisted of five tangent and six horizontal curve segments. The majority of the study sections along the closed course were Portland cement concrete pavement with the exception of the left curve approach to curves 2 and 3. The pavement markings were constant throughout the course; however, other reflectorized raised pavement markings (RRPMs), delineators, and chevrons were periodically changed out. The researchers used two illumination levels from the study vehicle to simulate additional traffic control device performance levels. The closed course is depicted in Figure 9.

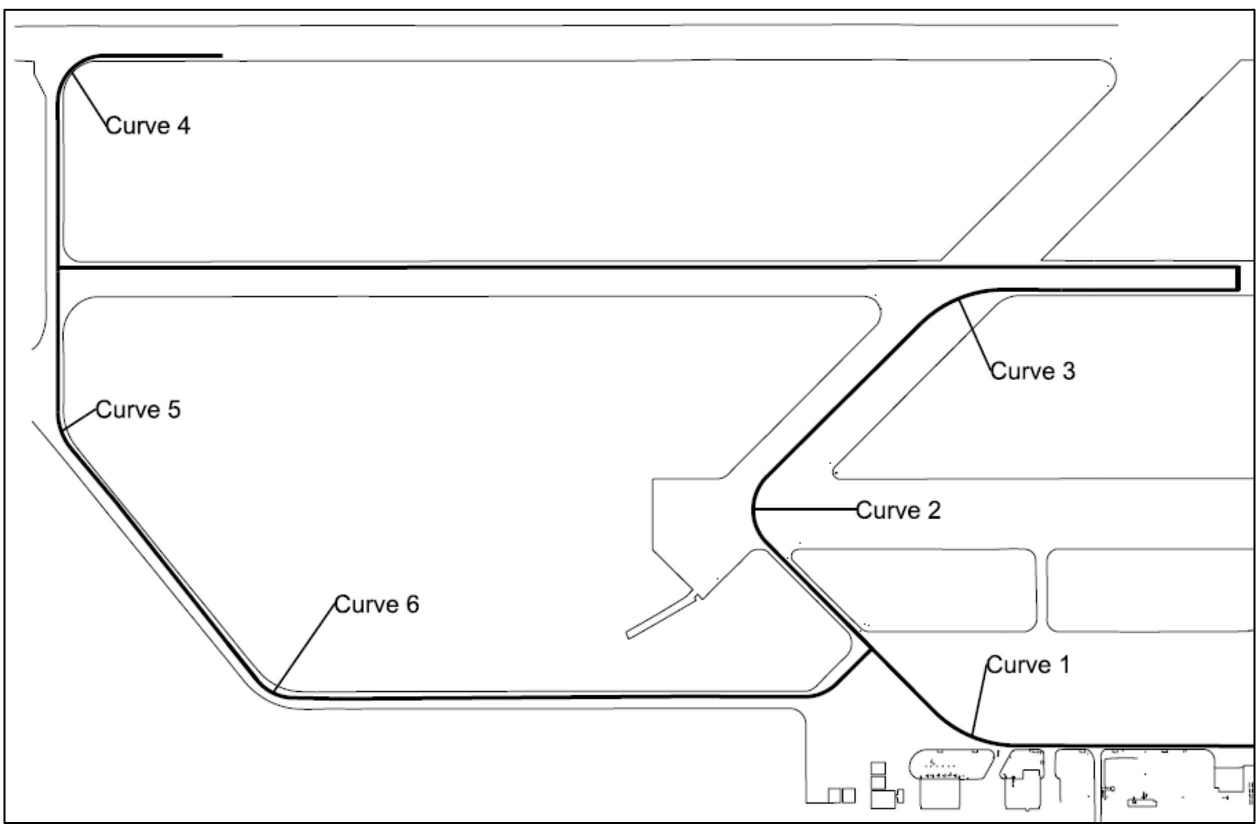


Figure 9. Closed Course.

Open-Road Course

The open-road course consisted of 21 miles of rural roadway just north of Riverside Campus. Figure 10 shows the open-road course, and the arrows indicate the portion of the course over which data were collected. The course took approximately 30 minutes to drive, and it consisted of a mixture of tangent and horizontal curve segments. All of the study segments consisted of asphalt cement concrete, but the pavement surface condition varied from relatively new to very old. The condition of the TCDs also varied throughout the course. On the open-road, only normal low-beam headlight illumination was used.

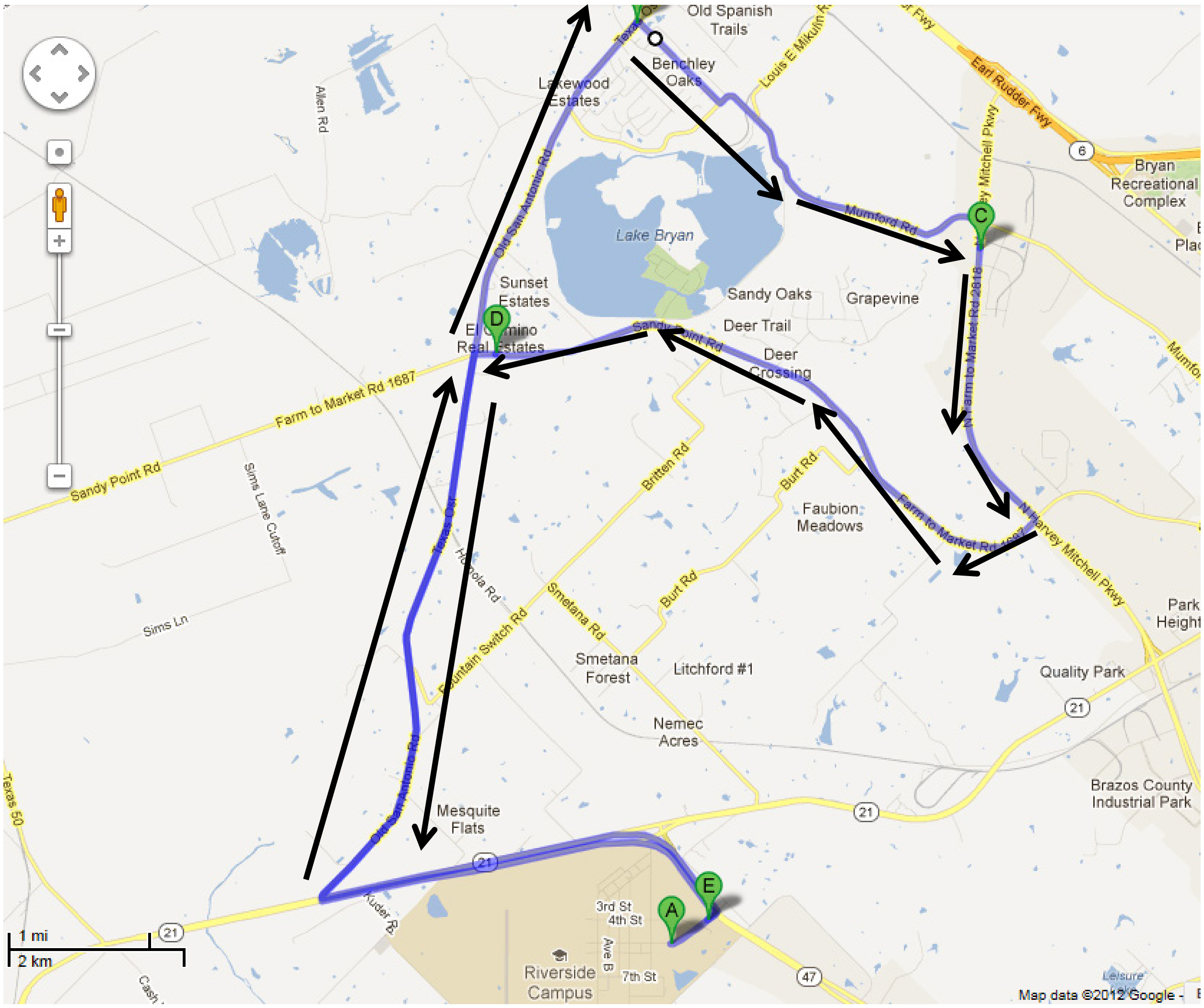


Figure 10. Open-Road Course.

Participants

The researchers collected data with 25 participants. There were 8 drivers that were between 18 and 35 years of age, and the other 17 participants were over 55 years of age. All of the participants will have 20/40 vision or better, and were not color-blind. Table 6 contains more detailed information on the distribution of the participants in the human factors study.

Table 6. Demographics Data.

Age Group	Mean Age (Std. Dev.)	Mean Visual Acuity	Gender (M/F)
18–35	26.0 (4.4)	20/15.6	3/4
55+	67.6 (8.8)	20/22	10/8

Procedure

Participants were scheduled to drive through a closed course route at the Texas A&M University Riverside Campus and open-road course route at night (see Figure 11). The participants were met at the entrance to the Riverside Campus by TTI staff and then escorted to an office where they completed an informed consent form, a demographics questionnaire, a Snell visual-acuity test, and a color blindness test.

Figure 11. Riverside Campus.

Prior to starting the study, the participants completed a few additional tasks. First, they were given some brief instructions about what was required of them. Provided they did not have any reservations about conducting the tasks described to them, participants were escorted to an instrumented vehicle. Once in the vehicle, they were given an opportunity to familiarize themselves with the controls of the vehicle (i.e., climate control, lights, and mirrors) and adjust the vehicle to individual preferences. Participants were instructed to wear a seatbelt at all times during the testing and to alert the researcher to any concerns throughout the study. They were also instructed to stop the vehicle at any point that they felt it was necessary.

The researcher guided each participant throughout the closed course. For the majority of the time during data collection, the researcher remained silent and allowed the participant to follow the direction of the pavement markings. At predesignated points, the researcher instructed each participant to rate the overall visibility of the TCDs on the road. The ratings were based on the visibility of the TCDs on a scale of 1 to 5, with 1 indicating that the TCD(s) provide an unsafe driving environment and need immediate replacement, and 5 indicating that the TCD(s) provide an outstanding driving environment and should be used throughout the state. Each participant was also encouraged to provide any supplemental comments on why he/she selected a specific rating based on the overall scene or specific TCDs. The researcher recorded the ratings of the TCD along the roadway segments throughout the course along with images associated with the ratings. At the end of each lap, each participant was asked to indicate if he/she had any general or specific comments with respect to the visibility of the TCDs. Participants were then instructed when to start any additional laps. Prior to starting a new lap, a researcher adjusted the headlights to the appropriate lighting level and other field crew staff changed treatments for the next lap.

After completing the fourth lap, each participant was directed to the open-road course. The researcher guided each person through the open-road course while recording rating data and their associated luminance images. The researcher prompted each participant when to rate the roadway. As with the closed course, ratings of tangent and horizontal curves were made. Once a participant completed the open-road course, he/she was directed back to closed course for an additional two laps. Once the closed course and open road testing concluded, each participant was directed back to the office where he/she was inducted, paid for his/her time, and escorted back off the premises.

In the end, each participant should have completed six closed course laps and one open-road lap. As the researchers had control over what treatments could be presented out at Riverside, they used a full factorial study design with:

- Two lighting levels (normal low-beam, and 50 percent of low-beam illumination in the far field beyond 100 ft in front of the vehicle).
- Three levels of RRPMs along the centerline (new, aged, and none).
- Two levels of edge lines (present and none).
- Two levels of chevrons in curves (present and none).
- Two levels of delineators in curves (present and none).

All of these results in 48 different treatments on horizontal curves sections (some curves were driven through more than once in a lap to ensure that all treatment combinations were achieved) and 12 different treatments on tangent sections (the number of laps required were dictated by the curve sample size requirements, so replications were achieved for the tangent segments).

Halfway through the study, the treatment order was changed as a form of pseudo-randomization.

DATA REDUCTION

The data reduction was carried out in four phases. The first phase consisted of reducing the geocoded subjective rating responses. Errors needed to be removed from the data set, and the sampling rate from the GPS data logger program resulted in data sets approximately 50 times larger than the actual response data. As the GPS data were trimmed, the researchers also merged the demographic data of each participant in the study. Once these data were reduced, the second phase was to pull the luminance images associated with each rating and reduce the images into grayscale output values. The fourth and final phase was to merge the grayscale luminance to the GPS ratings and demographics data. This process took considerably more time than originally anticipated and on average took approximately 40 hours per participant.

ANALYSIS

A categorical data analysis was completed to study the potential relationship between perceived nighttime driving comfort and the relative brightness and presence of each TCD meant for lane keeping. The dependent variable was the ordinal response reported by each study participant as he/she approached a variety of horizontal curve and tangent treatments. The ordinal response was a scalar value from 1 to 5 with:

- "1" indicating that the participant believed the roadway was not safe, and needed immediate improvement with respect to nighttime delineation from existing TCDs.
- "5" indicating that the participant believed the roadway was safe, and adequately delineated for nighttime driving.

The independent variables initially considered are listed in Table 7. The presence of centerline pavement markings was not evaluated because all roadway study treatments had centerline pavement markings. The data reduction method used to reduce the brightness of the centerline pavement marking brightness also captured the brightness of the RRPMs. However, this method did not allow for the brightness value of the RRPMs to be isolated. While this was possible, it was decided to assess the brightness of the delineation along the centerline of the roadway as a whole, because it was believed that drivers use pavement markings and markers as a system rather than isolated TCDs.

Table 7. Potential Independent Variables.

TCD	Presence	Relative Brightness			
		Average	Maximum	Minimum	Contrast
Centerline	No	Yes	Yes	Yes	Yes
RRPM	Yes	No	No	No	No
Edge Line	Yes	Yes	Yes	No	Yes
Delineator	Yes	No	Yes	No	Yes
Chevron	Yes	No	Yes	No	Yes

The researchers calculated contrast values to assess the visibility of specific TCDs viewed by each participant. The ratio of the relative brightness of one object versus its background is a common method to assess whether that object will be visible. As the ratio departs from 1, objects become more visible with values between 0 and 1 indicating a negative contrast and values above 1 indicating a positive contrast. The contrast values were generated by taking the average and maximum values and dividing them directly by the minimum values.

Only the presence and the maximum values were recorded for the delineator and chevron. The average values were not reduced, because it was not possible to devise a consistent method with the existing software that could be easily replicated. Table 8 details the descriptive statistics for the potential independent variables.

Table 8. Descriptive Statistics.

Location	TCD	Sample (n)	Relative Brightness			
			Average	Maximum	Minimum	Contrast[a]
Closed Course	Centerline	937	27.8	209.8	7.0	4.6/34.7
	RRPM		-	-	-	-
	Edge Line	527	78.38	182.9	-	13.2/31.2
	Delineator	168	-	2862.5	-	NA/454.3
	Chevron	130	-	1999.4	-	NA/371.0
Open Road	Centerline	600	29.1	318.7	5.9	5.9/57.5
	RRPM		-	-	-	-
	Edge Line	510	111.6	302.4	-	23.4/63.8
	Delineator		-	-	-	-
	Chevron	13	-	1645.2	-	NA/265.9

[a] Indicates Average Contrast Value/Maximum Contrast Value.

The results were categorized for the open road and closed course without consideration for participant age, gender, or visual acuity. The closed course included only Portland cement concrete versus asphalt-based road surfaces experienced on the open road, so it was believed that the contrast ratios may be different. Based on the values for the centerline and edge line pavement markings, the overall brightness of the pavement markings were brighter and the pavement surface dimmer on the open road course versus the closed course; the higher contrast values confirmed this. To further explore this point, the researchers graphed the overall rating response for the tangent treatments for the open road and the closed course in Figure 12. The graph shows that participants rated the open road treatments higher overall, which would support the idea that they prefer the higher pavement marking contrast values.

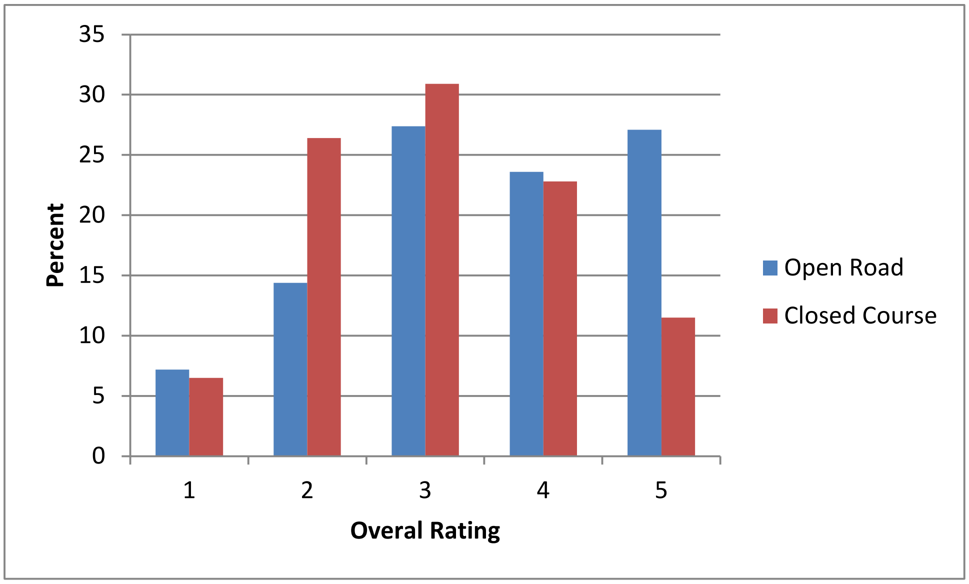


Figure 12. Open Road versus Closed Course Overall Rating for Tangent Treatments.

One consideration in roadway design is whether driver age impacts how a driver interacts with the roadway. As drivers age, their range of motion and visual capabilities decrease, so their reaction time increases. While the study design was not set up to assess this consideration, engineers typically consider designing for older drivers. For instance, it is common practice for transportation agencies to conduct nighttime inspections of TCDs using older drivers. The researchers collected data from older (e.g., 55 years of age and older) and younger drivers (e.g., 18 to 35 years of age), but their purpose in collecting a sample of younger drivers was solely to assess any potential differences between older and younger drivers. Table 9 shows that age group was a significant factor. The Pearson's Chi-Squared Test of Independence was carried out and shown to be significant, so the null hypothesis that younger drivers and older drivers are equally likely to rate TCD performance similar is rejected. Table 10 was populated to further investigate these differences, and it would appear that older drivers provided lower overall ratings than younger drivers with the exception of the centerline-only condition (e.g., no RRPMs or edge lines). The remainder of the analysis will be on the older driver participants.

Table 9. Significance Testing with Overall Rating and Age Group.

Age Group	Sample Size	1	2	3	4	5
18–35	409	10.5%	17.1%	30.6%	26.7%	15.2%
55+	1113	8.1%	25.9%	32.7%	19.6%	13.7%
Chi-Squared Test Statistic						19.57
Chi-Squared Test of Independence						0.001

Table 10. Overall Rating by Age Group along Tangent Treatments.

Age Group	TCD Treatment		Sample Size	OVERALL RATING				
	Edge Lines	RRPMs		1	2	3	4	5
18–35	**None**	**None**	10	10%	70%	20%	0%	0%
		Present	36	8%	11%	47%	33%	0%
	Present	**None**	48	4%	25%	25%	46%	0%
		Present	93	4%	5%	18%	28%	44%
55+	**None**	**None**	29	7%	48%	34%	10%	0%
		Present	101	7%	37%	34%	20%	3%
	Present	**None**	120	11%	28%	39%	18%	3%
		Present	263	6%	15%	27%	22%	30%

Table 11 shows the percent distribution of the overall ratings with respect to TCD treatments on curves, as rated by older participants. One key point is that participants never rated a centerline-only treatment as a 5. They reported more 5 ratings when either delineators or chevrons were present. While there were anecdotal participant comments throughout the study favoring RRPMs, the data suggest that the presence of edge lines may have a greater impact on overall rating. To further analyze the relationships between the potential independent variables and the dependent variables, the researchers used ordinal logistic regression.

Table 11. Overall Rating Distribution Based on Curve TCD Treatment.

TCD Treatment			Sample Size	OVERALL RATING				
Shoulder	**Edge Lines**	**RRPMs**		**1**	**2**	**3**	**4**	**5**
None	**None**	**None**	19	11%	58%	26%	5%	0%
		Present	82	11%	46%	26%	16%	1%
	Present	**None**	67	25%	42%	18%	7%	7%
		Present	210	10%	21%	36%	20%	13%
Delineator	**None**	**None**	20	0%	30%	35%	30%	5%
		Present	42	2%	21%	48%	19%	10%
	Present	**None**	37	3%	22%	41%	19%	16%
		Present	19	0%	5%	37%	32%	26%
Chevrons	**None**	**None**	10	0%	40%	30%	20%	10%
		Present	53	0%	23%	45%	21%	11%
	Present	**None**	19	0%	0%	42%	26%	32%
		Present	15	0%	13%	33%	33%	20%

Logistic Regression Models

Using SPSS 20, the researchers completed several different ordinal logistic regression analyses. The researchers tested to see whether the nominal presence values or the continuous grayscale luminance values generated a better fit. They tested several different two-way and three-way interactions. The final models used only the nominal values and no interactions for the tangent model and a combination of nominal presence values and contrast grayscale luminance values and no interactions for the curve model.

The researchers used several different techniques to assess the model fit, particularly the McFadden pseudo-R^2 test statistic and sum of the squared difference between the actual and the predicted values from the models. The McFadden test statistic ranges between 0 and 1, with the closer to 1 indicating a higher likelihood that the full model fits the data better than just the intercept model. When comparing multiple models to each other, the model with the higher McFadden test statistic would provide the better fit. For the other test comparison, the model with the smaller sum of the squared residuals would provide the better fit. In all cases during the analysis, the comparison of the McFadden test statistics and the squared residuals resulted in the same models having the same fit. The independent variables for each model and the resulting McFadden and squared residuals are shown in Table 12.

Table 12. Initial Model Comparison Results.

Model Parameter	Tangent			Curve		
	1	2	3	1	2	3
RRPM Presence	Y	N	N	Y	N	N
Edge Line Presence	Y	N	Y	Y	N	N
Delineator Presence	NA	NA	NA	Y	N	Y
Chevron Presence	NA	NA	NA	Y	N	Y
Maximum Centerline Contrast	N	Y	Y	N	Y	Y
Maximum Edge Line Contrast	N	Y	N	N	Y	Y
Maximum Delineator Contrast	NA	NA	NA	N	Y	N
Maximum Chevron Contrast	NA	NA	NA	N	Y	N
Sample (n)	513	513	513	596	596	596
Minimum (Difference[a])	−2	−4	−4	−3	−4	−4
Maximum (Difference[a])	2	2	2	3	2	3
Mean (Difference[a])	0.20	0.02	0.20	0.15	−0.02	0.23
Standard Deviation (Difference[a])	1.171	1.240	1.190	1.089	1.120	1.065
McFadden Test Statistic	0.041	0.019	0.029	0.028	0.045	0.046
Sum Squared Residuals[b]	723	788	745	720	746	705

[a] Indicates that this value is the residual difference calculated by subtracting the model *i* predicted rating value from the actual rating value.
[b] Indicates that this value was calculated by squaring the residual difference.

The researchers then reran the final models excluding a subset of the data from each model to test the predictive power of the model with data not included in the development of the model (see Table 13). The McFadden test statistics were slightly lower, but the researchers did not consider them practically different. The mean differences of the predicted values using the subset of data were lower with the minimum and maximum differences either the same or closer to zero. The standard deviations were smaller. The researchers also calculated the sum squared residuals; they were 57 for the tangent and 83 for the curve model predicted ratings on the subset of data. The researchers calculated the sum squared residuals divided by the sample size as another comparison. This was not a standard statistical comparison method, but the researchers believed it to be another way to compare the subset predicted model rating values to the predicted model rating values of the data used to generate the model. The values were considered similar.

Table 13. Final Model and Evaluation.

Model Parameter	Tangent			Curve		
	Estimate	Standard Error	Data Subset	Estimate	Standard Error	Data Subset
Threshold (Rating = 1)	−3.475	0.224	-	−4.410	0.341	-
Threshold (Rating = 2)	−1.607	0.142	-	−2.329	0.296	-
Threshold (Rating = 3)	−0.182	0.119	-	−0.785	0.279	-
Threshold (Rating = 4)	1.036	0.133	-	0.562	0.286	-
RRPM not Present	−1.063	0.188	-	-	-	-
Edge Lines not Present	−1.126	0.198	-	-	-	-
Maximum Centerline Contrast	-	-	-	0.004	0.001	-
Maximum Edge Line Contrast	-	-	-	0.011	0.002	-
Delineator not Present	-	-	-	−1.170	0.208	-
Chevron not Present	-	-	-	−1.391	0.226	-
Sample (n)	472	-	41	545	-	51
Minimum (Difference[a])	−2	-	−2	−4	-	−2
Maximum (Difference[a])	2	-	2	3	-	2
Mean (Difference[a])	0.28	-	-0.66	0.29	-	−0.76
Standard Deviation (Difference[a])	1.160	-	0.990	1.062	-	1.031
McFadden Test Statistic	0.043	-	-	0.045	-	-
Sum Squared Residuals[b]	670	-	57	644	-	83
Sum Squared Residuals/Sample	1.4	-	1.4	1.2	-	1.6

[a] Indicates that this value is the residual difference calculated by subtracting the model *i* predicted rating value from the actual rating value.
[b] Indicates that this value was calculated by squaring the residual difference.

The researchers then completed a sensitivity analysis on the final models. This was completed to evaluate whether changes to a specific TCD had a greater impact on the rating than others. It was assumed that TxDOT would choose not to make any changes to the TCDs along a segment of roadway if the overall rating was 3 or higher within a given fiscal year, so only predicted overall ratings of 1 to 2 were tested. However, to start this analysis, the researchers first evaluated a range of results collected from the field data. The input test values were:

- Edge line presence along tangents and curves (present, not present).
- Delineator presence along curves (present, not present).
- Chevrons presence along curves (present, not present).
- Maximum centerline contrast along tangents and curves (3, 75, and 750).

This was critical, because the results supported changing the tangent model from a completely categorical to mixed model 3 in Table 12 that used the independent variables: the continuous maximum centerline contrast and the nominal right edge line presence. When the initial sensitivity analysis was carried out on the tangent model with nominal input values, the range of the output values was 2 to 3. This was not considered practical when considering there were several instances of reported values of 4 and 5 along the tangent treatments. Subsequently, the researchers conducted a sensitivity analysis on tangent model 3, and curve model 3 that each model predicted overall ratings between 2 and 5. Table 13 was then revised and tabulated in Table 14.

Table 14. Revised Final Models.

Model Parameter	Tangent			Curve		
	Estimate	Standard Error	Data Subset	Estimate	Standard Error	Data Subset
Threshold (Rating = 1)	−2.819	0.212	-	−4.410	0.341	-
Threshold (Rating = 2)	−0.971	0.133	-	−2.329	0.296	-
Threshold (Rating = 3)	0.418	0.125	-	−0.785	0.279	-
Threshold (Rating = 4)	1.603	0.148	-	0.562	0.286	-
RRPM not Present	-	-	-	-	-	-
Edge Lines not Present	−1.045	0.197	-	-	-	-
Maximum Centerline Contrast	0.007	0.002	-	0.004	0.001	-
Maximum Edge Line Contrast	-	-	-	0.011	0.002	-
Delineator not Present	-	-	-	−1.170	0.208	-
Chevron not Present	-	-	-	−1.391	0.226	-
Sample (n)	472	-	41	545	-	51
Minimum (Difference[a])	−2	-	−2	−4	-	−2
Maximum (Difference[a])	2	-	2	3	-	2
Mean (Difference[a])	0.28	-	−0.49	0.29	-	−0.76
Standard Deviation (Difference[a])	1.160	-	0.952	1.062	-	1.031
McFadden Test Statistic	0.029	-	-	0.045	-	-
Sum Squared Residuals[b]	701	-	46	644	-	83
Sum Squared Residuals/Sample	1.5	-	1.2	1.2	-	1.6

[a] Indicates that this value is the residual difference calculated by subtracting the model *i* predicted rating value from the actual rating value.
[b] Indicates that this value was calculated by squaring the residual difference.

Using these two revised models, the researchers then evaluated the impact of changing the independent variables associated with specific responses of 1 and 2 to see what could be done to improve the overall rating to 3 or higher. For horizontal curves, the addition of either delineators or chevrons would automatically improve the predicted overall rating to a 3 or higher depending on the maximum contrast brightness of the centerline/RRPMs or edge lines. It appears that replacing the centerline delineation or edge line delineation can have a greater impact in the predicted overall rating provided by the curve model than delineators or chevrons. For the tangent model, the addition of edge lines will put the predicted overall rating to a 3 or higher depending on the maximum brightness of the centerline/RRPMs. As with the curve model, it is the contrast brightness that has the greatest impact in the model, but this time solely through the maximum contrast brightness of the centerline/RRPMs.

CHAPTER 5:
LEVEL OF SERVICE

Level of service of existing traffic control devices must be tied to a measurable metric. The researchers considered retroreflectivity, luminance, and contrast ratios of these properties. Retroreflectivity has strong consideration because minimum retroreflectivity levels of newly installed TCDs are established by states for quality control, and because FHWA has already accepted minimum retroreflectivity requirements for aged-in-service traffic signs. However, mobile measurements of the retroreflectivity of TCDs have proven difficult to do effectively without expensive and elaborate equipment that require highly technical staff to operate (*1*). Furthermore, existing retroreflectivity requirements are all tied to specific geometries that may not be experienced by drivers and may be problematic to measure with respect to the driving condition. Subsequently, the researchers focused their efforts on developing a mobile luminance system and used it to gather TCD rating data to develop an LOS framework based on human factor ratings of TCDs and their associated luminance values.

Considering the capabilities of the prototype mobile luminance measurement system and models developed from the human factors study discussed in Chapter 4, the researchers developed a framework for conducting nighttime inspections to assess level of service of existing traffic control devices along rural two-lane roadways. The researchers considered two approaches to the nighttime inspections: precise measurement and approximate measurement.

Precise Measurement Method

The precise measurement method would utilize continuous image data collection. Using this method, each district would drive its roadways and record images continuously, then post-process the images. This process would require a considerable amount of time to complete without the development of an automated method to reduce the images, which was not able to be developed within the scope of this project. One of the primary benefits of this method would be the ability to have a record of the current state of the entire roadway network.

The researchers did a feasibility calculation on recording images for all roadways throughout the state. The following assumptions were made to simplify this calculation:

- All two-lane, two-way roadways.
- Total centerline mileage was approximately 80,000 miles.

- Data must be collected in both directions (approximately 160,000 miles).
- Data collection speed of 60 mph and assuming no stops or other delays (approximately 2,700 hours of driving).
- Only driving at night and averaging 8 hours a night (approximately 340 days).
- Only driving on Sunday through Wednesday to avoid higher traffic volumes and minimizing exposure to intoxicated drivers (approximately 85 weeks to collect the data).
- Record 1 image every quarter mile. Must capture in-lane TCDs and right shoulder TCDs with one image, which would be approximately 1.5 MB (approximately 640,000 images and 1 TB of data).
- A very conservative estimate to reduce 1 image every minute (approximately 640,000 minutes to reduce the data).

Based on the above bullets, it is believed that it would take at least two data collection vehicles running 43 weeks each year to collect the data. When considering that TxDOT districts already conduct annual nighttime inspections of their roadways, this would not appear to be any additional expense. However, it is projected that an additional 45 weeks for two employees to reduce the data would far exceed what districts already do to report TCD failures for planning purposes.

Even so, the data gained from this method could be incorporated into an LOS for planning purposes. Using the 1 through 5 category rating, as established in the human factors study, the reduced data could be input in the tangent and curve models, respectively. A rating of 3 would be considered passing and would require no immediate action, but roadways segments rated at 1 or 2 would require maintenance to bring them back to within acceptable limits, as established from the human factors study described here. These models could even be used to investigate whether only one TCD needs to be modified, such as adding/restriping just an edge line.

Approximate Measurement Method

The approximate measurement method requires the data collection staff to conduct on-screen, real-time processing. One staff member would drive the vehicle, and another staff member would monitor incoming images of the forward road scene. Each image would be analyzed in real-time using threshold settings that would correlate to acceptable luminance levels that human factors data have established, or luminance levels based on calibrated samples at or near the minimum in-service retroreflectivity levels that TxDOT and/or FHWA required. As the human factors data were collected in a specific vehicle that TxDOT does not use, this limits any direct comparisons between the luminance from the human factors data and the luminance that would be recorded in the field. While there are methods to mitigate this concern, it is also possible to use existing minimum in-service retroreflectivity levels.

TxDOT could construct or purchase calibration sign and pavement marking samples near established minimum retroreflectivity levels, then measure the samples under driving conditions. Those images could be used to calibrate unique threshold values to each vehicle that would be used to conduct nighttime TCD inspections. Once the thresholds are set for the different TCDs to be encountered, such as white edge lines pavement markings, yellow centerline pavement markings, and right shoulder mounted white signs, the staff member collecting the data would monitor processed images to verify if the TCDs in the images were meeting or exceeding requirements based on whether their reported values were at or above the thresholds. The data collector would periodically record images of good and bad segments for storing and to report what segments met requirements and what segments required some annual maintenance. So, the approximate measurement method would be used in a simple pass/fail criteria LOS model.

CHAPTER 6: SUMMARY AND RECOMMENDATIONS

TTI developed a prototype mobile luminance system and conducted a human factors study on the TCDs to develop a framework LOS for TCDs along rural two-lane roadways using objective field measurements. The mobile luminance system consisted of two 12-bit monochromatic cameras with V lambda corrected filters and Fujinon megapixel lenses. The system also included GPS to geocode the incoming image data to within ±2.5 meters. The current system is limited to 1 Hz operation when several advanced thresholding features are used to conduct semi-automated analysis in real time.

The human factors study was conducted at the Texas A&M University Riverside Campus and on a nearby open-road roadway network. There were 25 participants with emphasis on the analysis of the 18 participants aged 55 years and older. Each participant rated on a scale of 1 (e.g., poor performance requiring maintenance) to 5 (e.g., outstanding performance, not requiring any maintenance) a minimum of 40 different closed-course and 30 different open-road TCD treatments. All treatments included centerline pavement markings, but differed between the presence of RRPMs along the centerline and the presence of edge lines. Delineators or chevrons were also possible along the outside shoulder of horizontal curves.

In general, participants subjectively stated liking RRPMs, edge lines, and chevrons. Objectively, however, the data confirmed some points while only partially supporting others. While chevrons were noted as favorable to delineators, the impact in the curve model shows that the installation of delineators and chevrons will improve the overall rating of a curve, but that the improvement had a similar impact on the model regardless of device used. In other words, the curve model did not capture the subjective preference of participants to chevrons over delineators. The fact that both models use maximum centerline brightness contrast versus average brightness contrast supports the idea that RRPMs supplementing the centerline are preferred. While edge lines had a smaller impact along tangent treatments, they still resulted in improving the overall rating of a particular TCD treatment regardless of whether the treatment was along a tangent or a curve.

From these findings, the researchers developed two possible LOS methods that TxDOT could use to supplement their current nighttime inspection method. The precise measurement method uses the mobile luminance system. TxDOT would record continuous images at 1 Hz or lower frequency and the images would be post-processed using the models developed from the human factors study. A rating of 3 or better would not require any scheduled maintenance within the coming fiscal year, while ratings of 1 or 2 would require action. The models could be used to assess what roadways require maintenance, and could even be used to indicate what specific maintenance would be required, such as only adding or restriping an edge line. The approximate measurement method also uses the mobile luminance system, but a smaller sample of images would be recorded rather than post-processing because data collectors would use the thresholding interface to make real-time objective visual assessments of the TCDs. This method would use a pass/fail rating.

The researchers want to emphasize the word "supplement," because it is believed that while the current nighttime inspection method TxDOT used to assess the visibility of TCDs is subjective, multiple studies (*27, 31, 31*) have shown this method to be effective in terms of conservative and timely assessments. Several recommendations are stated with regard to implementation and further research.

RECOMMENDATIONS

Researchers recommend the following:

- Use the precise and approximate measurement methods in conjunction with nighttime inspections and retroreflectivity measurements to assess the accuracy and repeatability versus time.
- When using the precise method, compare the prescribed treatment along roadway segments based on curve and tangent assessments versus tangent segments only. It is more cost effective with respect to time and money, and more likely to match current requirements and practices with respect to TCDs. For instance, it is unlikely that districts would add delineators in a curve that did not already have them, because delineators should be installed based on the severity of the curve.
- Revise the system to accommodate automation with regard to TCD detection, evaluation, and recommended maintenance.
- Consider the integration of 3-dimensional scanning LiDAR. Significant advances have occurred to measure distance from an object using LiDAR, and it will soon be possible to measure distance to roadside TCD hardware more efficiently in a manner

that would help with generating more accurate inventories and potentially improve the likelihood of full automation in the post-processing stage.

- Consider the integration of a motorized varifocal lens with a motorized iris to better accommodate on-the-fly in-field system adjustments that are traceable and minimize error.

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