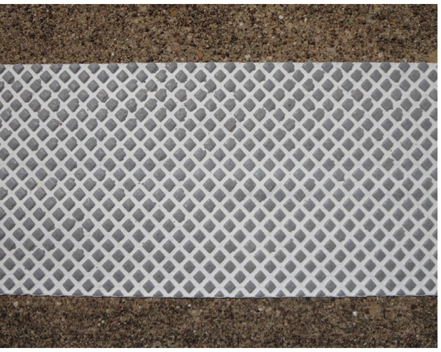
SAFER ROADS SAVE LIVES

EVALUATION OF THE EFFECTS OF PAVEMENT MARKING WIDTH ON DETECTABILITY BY MACHINE VISION: 4-INCH VS 6-INCH MARKINGS

PREPARED FOR THE AMERICAN TRAFFIC SAFETY SERVICES ASSOCIATION



American Traffic Safety Services Association
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FINAL REPORT

Prepared for the
American Traffic Safety Services Association

Adam M. Pike, P.E.
Timothy P. Barrette, Ph.D.
Texas A&M Transportation Institute
The Texas A&M University System
College Station, Texas

Paul J. Carlson, Ph.D., P.E.
Road Infrastructure Inc.
College Station, Texas

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DISCLAIMER

The opinions and conclusions expressed or implied in the report are those of the research agency. They are not necessarily those of the American Traffic Safety Services Association.

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ABSTRACT

This study explores the effect of longitudinal pavement marking width on the detectability of preformed tape pavement markings by a machine vision (MV) based advanced driver assistance system (ADAS). More specifically, this research compares the performance of MV technology relative to 4-inch and 6-inch wide pavement markings. An aftermarket advanced driver assistance lane departure warning (LDW) system was adapted such that the pavement marking detection confidence rating that the LDW algorithm assigned to each pavement marking was extracted. The detection confidence rating assigned to each pavement marking served as the measure of the detectability of the pavement markings. Variations of 4 and 6-inch wide preformed pavement marking tape were manufactured and installed on a closed course testing area to simulate different levels of in-service markings. The testing included combinations of lighting (daytime, nighttime, and nighttime with on-coming headlamp glare) and environmental conditions (dry and wet recovery).

This research shows that the 6-inch wide longitudinal preformed tape markings consistently improved MV detection performance under wet daytime conditions, which is critical since wet daytime conditions provide a significant challenge for the MV technologies tested. Combined with results from the on-going NCHRP 20-102 (06) research, 6-inch wide lane line markings can also be expected to improve MV detection performance as vehicle speed increases (based on testing at speeds of 40, 55, and 65 mph). Other conditions where 6-inch wide longitudinal pavement markings may potentially improve MV detection performance as compared to 4-inch wide markings are the following areas where potentially conflicting signals may confuse MV systems from detecting and tracking the markings: areas with remnants of previously removed markings, pavement scarring due to removal activities, blackout markings, crack seal, longitudinal seams in the pavement, varying road surfaces, cracking, rutting, or areas where glare is common and impacts marking visibility.

EXECUTIVE SUMMARY

Advanced driver assistance systems (ADAS) such as lane departure warning (LDW) and lane keeping assistance (LKA) are becoming more common features on newer model vehicles [1]. The original introduction of ADAS in high-end vehicles has been followed by gradual market growth that is expected to continue [2]. LDW and LKA typically use machine vision (MV) technology in the form of cameras connected to computers equipped with lane detection software. In the past, research addressed improving ADAS quality by enhancing MV algorithms to account for the variability of real-world driving scenarios; however, focusing only on the MV hardware and software is only investigating one side of a two-sided problem. Pavement marking standards and policies are typically written with the human driver in mind, but with vehicles already on the road capable of low-level autonomy (such as LDW and LKA) and the industry on the precipice of incorporating vehicles capable of higher-level autonomy into the traffic mix, it is important to also consider what characteristics of roadway infrastructure play critical roles in the efficacy of ADAS and other autonomous vehicle (AV) systems.

This study explores the effect of longitudinal pavement marking width on the detectability of preformed tape pavement markings by a MV based LDW system. More specifically, this research compares the performance of MV technology relative to 4-inch and 6-inch wide pavement markings. An aftermarket ADAS LDW unit was adapted such that the pavement marking detection confidence rating that the LDW algorithm assigned to each pavement marking was extracted. The detection confidence rating assigned to each pavement marking served as the measure of the detectability of the pavement markings. Eight preformed pavement marking tapes with varying levels of color and retroreflectivity, to simulate different levels of in-service markings, were observed as 4 and 6-inch wide markings under six combinations of lighting and environmental conditions: daytime dry, daytime wet, nighttime dry, nighttime dry with glare, nighttime wet, and nighttime wet with glare. The wet conditions were wet recovery conditions, i.e. the evaluation took place after the markings and pavement were wetted, but not while being wetted. The nighttime glare condition was on-coming headlamp glare from an opposing vehicle.

This study took place on a closed course, with a series of preformed tape pavement markings installed on a runway at the Texas A&M University System's RELLIS Campus. The markings were placed in a similar fashion to the way markings would be placed on a typical roadway section creating a 12 foot wide travel lane. Researchers compared the detection confidence rating data collected from the MV units with data collected using a charge-coupled device (CCD) camera, handheld retroreflectometers, and a handheld spectrophotometer. These additional instruments were used to assess the performance characteristics of each of the pavement marking samples.

The results of the research show that 6-inch wide preformed tape pavement markings provide higher levels of detection confidence, for the ADAS LDW unit tested, in some but not all scenarios compared to 4-inch wide markings. It is important to keep in mind that MV systems perform differently than human eyes; in conditions where the MV system did not detect 6-inch markings any better than 4-inch, it is possible a human eye would have. In dry daytime and nighttime conditions with 4-inch wide markings in a good state of repair (i.e., markings with retroreflectivity, color, and contrast levels that would generally not be deemed inadequate by

today's practices or standards), the performance of the MV LDW system was high; and in these cases, the increased width of 6-inch markings had no measurable impact. The research showed that 6-inch wide markings improve MV LDW performance when the detection of 4-inch markings was more difficult. In particular, wet daytime conditions were found to be a challenge for MV LDW pavement marking detection. In this case, 6-inch markings consistently improved the MV LDW pavement marking detection performance. The MV LDW performance in wet nighttime was consistently better than in wet daytime conditions, which was unexpected but possibly caused by the vertical profile of the pavement marking tape used to conduct this study. The pavement marking tape was manufactured with various levels of retroreflectivity and shades of white and yellow. The intent was to have the ability to control these factors in a uniform and repeatable way. However, this approach also led to inherent limitations. As described, the pavement marking tape included a profiled design, which provides a way for the markings to drain quicker than a more typical flat marking (the vast majority of markings in the US are flat markings, with no vertical profile). Also, the tape provided well-defined longitudinal edges that represent newly installed markings and not markings that have been in the field for any considerable length of time (pavement markings wear from the top and also the edges, leading to in-service markings less than 4-inches wide and also having inconsistent edges). This may have also led to some limitations in this study since MV LDW systems generally look for sharp edges of longitudinal contrast differential as a primary method for detecting pavement markings.

Parallel and on-going research has also been underway to evaluate the characteristics of pavement markings that affect MV LDW detectability (NCHRP 20-102(6)). The NCHRP study also showed that wet daytime conditions were a challenge for MV ADAS performance. In addition, the NCHRP study also identified other scenarios where MV ADAS performance may benefit from 6-inch wide pavement markings. For instance, it was found that higher speeds and lower contrast reduced MV LDW detectability of 4-inch markings. It was also found that lane line markings had lower detection confidence levels than comparable edge line markings. Glare was also shown to reduce the MV LDW performance (daytime and nighttime). Based on the study results obtained for the current work, these are examples of other conditions where 6-inch wide pavement markings may improve MV LDW performance. Other conditions where 6-inch wide longitudinal pavement markings may potentially improve MV detection performance as compared to 4-inch wide markings are the following areas where potentially conflicting signals may confuse MV systems from detecting and tracking the markings:. areas with remnants of previously removed markings, pavement scarring due to removal activities, blackout markings, crack seal, longitudinal seams in the pavement, varying road surfaces, cracking, rutting, or areas where glare is common and impacts marking visibility.

The results of this study and the companion NCHRP study suggest that the most critical component of detectability of pavement markings by MV systems is contrast. When adequate contrast between the pavement and the marking exist, the MV system is able to determine the boundaries of the lane with a high degree of confidence.

The researchers recommend that 6-inch wide markings be considered in broken lane line areas with speeds of 65 mph or greater. Based on the on-going NCHRP 20-102 (06) study, observations taken at 65 mph tended to have lower MV confidence ratings than those taken at 50 mph, and broken lane line areas showed lower detection confidence levels than edge line markings. 6-inch wide markings (edge line, center line, lane line) should be considered in areas where run-off-the-road crashes are common. The research presented herein shows benefits to the MV system detection and literature shows improved safety for human drivers when 6-inch wide markings are implemented. The researchers recommend that 6-inch wide markings be considered in areas where rain and wet conditions are common. The researchers also recommend that 6-inch wide markings be considered in areas where conflicting signals may confuse MV systems from detecting the markings, i.e. areas with previously removed markings, blackout markings, crack seal, varying road surfaces, cracking, rutting, or glare.

There are several areas where follow up research has been suggested. As described above, the pavement markings used for this study were made with profiled tape. Additional research should explore the impacts of worn markings more representative of in-service markings with the following topics in mind:

- Flat markings – Paint and thermoplastic make up the vast majority of pavement marking materials in the US. The profiled tape markings used in this study are elevated above the wet pavement surfaces and may subsequently perform better than those that are installed flush with the pavement.
- Lower visibility markings – During this study, most of the markings performed well regardless of contrast ratio. Future research should investigate the minimum contrast needed for MV detection and the role of marking width in detection at low visibility levels. The research should again consider a variety of materials, including tape, paint, and thermoplastic, to assess if the material type plays a role in detectability.
- Worn edges – The tape markings used in this study were modified to have reduced visibility properties in comparison to new markings, however, the edges remained well defined (perfectly straight) which is inconsistent with the in-service markings wear.
- Wider markings – The markings examined in this study are considered to be standard width by the MUTCD. Wide markings (8 or more inches) may have a more pronounced benefit compared to 4 or 6-inch wide markings.
- Contrast markings – Faded asphalt road surfaces, depending on the severity, as well as light-colored concrete pavement, may necessitate the use of contrast markings for MV detection. Understanding what level of fading must occur for contrast markings to be more detectable than standard markings is a necessary step to identify cost-effective installation
- MV systems – Future studies could look to replicate the findings of this study with different MV technologies. MV systems are rapidly evolving and largely proprietary in nature. The performance of different systems may be subject to variability in effectiveness. Newer systems may look further down the roadway than the system used in this study, and therefore may benefit from 6-inch wide markings more so than the current system, as 6-inch wide markings are primarily intended to improve visibility at longer distances.

Beyond the suggested research topics, continued effort is needed to promote and support an open dialogue, between the various groups that are affected by these new technologies. Agencies and industry on the infrastructure side and suppliers and OEMs on the MV side. Industry groups such as the American Traffic Safety Services Association (ATSSA), Automotive Safety Council (ASC), and SAE International can help bridge the gap between government and industry to improve collaboration and advancement of these technologies.

CHAPTER 1. INTRODUCTION

In the relatively recent past, MV has been shown to be a versatile tool in tackling a wide variety of problems facing the transportation industry. MV applications are becoming increasingly common in the automotive industry, specifically for crash avoidance and lane departure prevention. As the automobile industry continues to push the envelope on AVs, continued development and improvement of these systems is critical. While the burden of developing and improving the systems, both on the hardware and software side, will fall squarely on automobile manufacturers and their suppliers, the role of ensuring that adequate infrastructure is in place to facilitate the deployment of AVs will largely fall on local, state, and national-level transportation agencies.

The National Cooperative Highway Research Program (NCHRP) sponsored a research project 20-102 (06) that was conducted by the Texas A&M Transportation Institute. The NCHRP research specifically investigated how various qualities of longitudinal pavement markings affect their detectability by MV hardware, with the overarching idea of developing recommendations to ensure that the pavement markings are detectable by both humans and camera-based detection systems. The NCHRP project is centered on the investigation of marking material properties, such as coefficient of retroreflected luminance (R_L) and CIE Y luminance, but the physical dimensions of the markings were beyond the scope of that study. To supplement the research funded by the NCHRP, the American Traffic Safety Services Association has funded this study, which specifically investigates the effect of pavement marking width on marking detectability by MV systems.

The existing body of research on the effect of pavement marking width on detectability has unsurprisingly been centered around the human driver, and results on the effect of pavement marking width have been somewhat mixed until recently. A Virginia study from the mid-1980s examined several run-off-road crash types and found no evidence that wide edge lines significantly affected the incidence of these types of crashes [3], as did a similar study in New Mexico [4]. Several studies have focused on older drivers when evaluating pavement marking width, including a field study conducted by researchers at the University of Iowa at the onset of the 21st century. This study found no evidence that pavement marking width affected the distance at which study participants could detect pavement markings [5]. A study funded by the American Association of Retired Persons found that study participants generally felt that wide (8-inch) markings affected the way they drove and aided in lane keeping [6]. In 2002, researchers at TTI conducted a comprehensive review of the literature on specific measures of effectiveness typically used to evaluate pavement markings. The authors of the study suggest that the greatest benefit of 6-inch wide pavement markings is realized at the following locations: horizontal curves, segments with narrow or no shoulders, work zones, roadways where low luminance contrast of markings is common, and areas where there is a high prevalence of older drivers [7].

TTI conducted a multifaceted study in 2010 on longitudinal pavement markings at a time when states were generally increasing the use of 6-inch wide markings in place of the standard 4-inch wide pavement markings. A closed course study evaluated the effect of pavement markings on vehicle lateral placement, speed, and lane-keeping glances. Participants tended to shift away from edge lines as the edge line marking width increased along tangent sections with small alignment shifts. Additionally, the likelihood of edge line encroachment decreased by 60 percent and the percentage of non-lane keeping glances decreased [8]. The 2010 TTI study also included a cross-sectional analysis of Illinois crash data and an empirical Bayes before-after analysis of Michigan crash data that pavement markings wider than 4-inches (5-inch in Illinois and 6-inch in Michigan) were associated with decreased crash rates of particular types of crashes, including fatal crashes [8].

TTI led a Federal Highway Administration project which included an investigation into the safety and operational effects of 6-inch wide pavement markings [9]. The previously described Michigan and Illinois data were expanded and combined with data from Kansas and revisited in the report and subsequent paper which used an interrupted time series, cross-sectional, and empirical Bayes analyses, respectively. The results illustrate improved safety associated with edge line markings wider than 4-inches on two lane rural highways [9, 10]. A crash severity analysis on the two data sets found that a reduction in the proportion of higher severity crashes was associated with wider than 4-inch edge line markings [9]. The observational study of driver behavior through curves conducted in Tennessee could not identify consistent trends in driver behavior due to marking width [9].

Another TTI study conducted a benefit/cost analysis of wider than 4-inch edge line markings and other roadway safety features designed to prevent run-off-the-road crashes. Wider than 4-inch edge lines were shown to have a benefit/cost ratio ranging between 43.96:1 to 21.72:1 considering fatal crashes and 11.24:1 to 11.16:1 considering injury crashes [11]. Ultimately, the body of research literature for pavement marking width does not demonstrate a consistent effect on operational measures (such as speed or lateral lane positioning), however, there is a positive safety effect in terms of reduced roadway departure crashes, especially on two-lane, two-way highways.

Now, with the increased prevalence of technology in the vehicle, the research focus is shifting from the traditional measures of operational and safety effects, to the effects on vehicle technologies. Recent research has evaluated pavement markings for MV systems using a stationary vehicle. The research found that the width of pavement markings generally resulted in increased detectability by MV systems, particularly at longer distances [12]. Caltrans has announced that they are now replacing 4-inch wide markings with 6-inch wide markings, using more durable marking materials (e.g., thermoplastic and methyl-methacrylate), and removing Botts' Dots (non-reflective markers) [13]. The new wider and brighter markings are expected to enhance safety for older drivers and truckers, and be more visible in conditions such as rain. The Caltrans article also notes that based on consultations with Tesla and Google, the new markings should provide a better roadway guide for autonomous vehicles.

CHAPTER 2. RESEARCH APPROACH

This research identified differences in longitudinal pavement marking (i.e., pavement marking edge lines) detectability by the MV system when marking width changed from 4 to 6 inches. According to the MUTCD, longitudinal pavement markings are considered to be normal lines if the width is between 4 to 6 inches, while wide lines are at least twice the width of a normal line [14]. It is common practice to refer to 6-inch wide markings as wider markings. In this document 6-inch wide markings will be referred to as 6-inch wide markings so that there is no confusion with markings wider than 6-inches. Various longitudinal preformed tape pavement markings were evaluated using an aftermarket MV system that was installed on two different vehicles. The following section describes, in detail, the equipment and approach used to collect and reduce data for this project.

FACILITIES

Data collection activities for this study were conducted at the Texas A&M University System's RELLIS campus. The facility, which was previously an Air Force base, has a network of runways and taxiways that served as the testbed for the evaluations as the research team has substantially more control over the characteristics of the markings than would be available in a field test setting and researchers are unencumbered by the presence of other road users. Utilizing a closed course test facility does limit the study in several ways. First, the markings have not been degraded by weather (due to the duration of the study) or traffic. Second, the concrete pavement is relatively consistent throughout the facility. Concrete is generally lighter in color than asphalt, which means that marking samples will have different contrast ratios on different pavement surfaces. The test areas had a one percent cross slope to facilitate drainage.

Data were collected in two phases, with Phase I of data collection activity occurring during winter of 2016, while Phase II data collection activity occurring during summer of 2017. The specific timeframe of the data collection is an important factor due to the changes in the position of the sun, and its impact on day time data collection.

Figure 1 presents the location of the approximately 1-mile long runway testing area used for data collection. Additional information on the preformed tape pavement markings samples applied to the test area is provided later in this chapter.

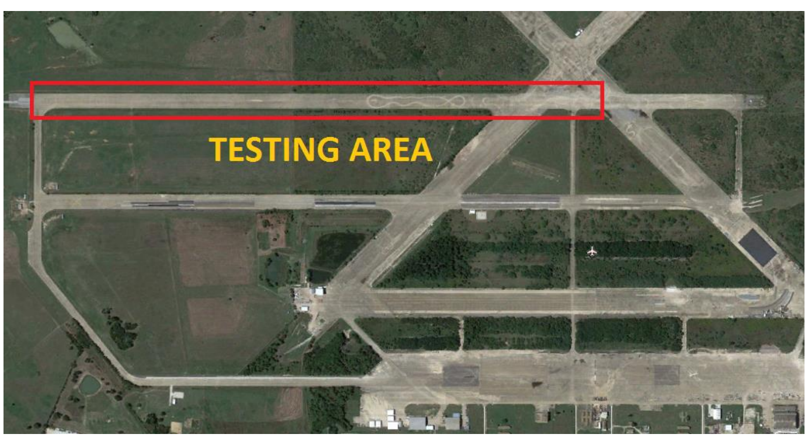


Figure 1. Pavement Marking Testing Area at RELLIS Campus

ROADWAY AND AMBIENT LIGHTING CONDITIONS

Six scenarios representing various lighting and moisture conditions were considered: daytime dry, nighttime dry, nighttime dry with glare, daytime wet, nighttime wet, and nighttime wet with glare. The wet conditions were wet recovery conditions, i.e. the evaluation took place after the markings and pavement were wetted, but not while being wetted. When appropriate, condition specific data were matched to each condition. For example, luminance was measured separately for daytime and nighttime observations during each data collection period.

To simulate wet road conditions, a truck was used to tow a modified tanker trailer that applied water to the roadway surface. This water temporarily flooded the markings and road surface. Figure 2 provides an image of the truck applying water to a marking test section.

Figure 2. Water Distribution System on Semi-Trailer

EQUIPMENT

Vehicles

Two vehicles, a 2015 Ford Explorer and a 2015 Ford F-150 were used to collect data for this project. Figure 3 provides images of the two test vehicles. The Explorer was used in both phases of the study to collect data at 50 and 65 miles per hour during the various evaluation conditions. The F-150 was only used during Phase 2 data collection. The F-150 collected data at 50 or 65 mph in dry conditions during both day and night evaluations. During night observations, both vehicles only used low beam illumination. The headlights on both vehicles were the standard OEM headlights with halogen bulbs. During night glare testing the F-150 served as the glare vehicle with low beam illumination. The truck was stationary near the end of the test markings being evaluated, in a position representing an opposing vehicle in a two-lane two-way alignment.

Figure 3. Ford Explorer and F-150 Used for Data Collection

Machine Vision System

Both vehicles used in this study were outfitted with a Mobileye 5 series advanced driver assistance system. Figure 4 shows the Mobileye system and additional forward-facing camera to capture the forward scene during data collection.

The Mobileye system uses a monochrome camera (<1 megapixel) that focuses on pavement markings located 30-50 feet in front of the vehicle. Initial testing to determine when the start or end of a marking test section was detected indicated the 30 to 50 foot range. A paper describing a test with the same ADAS equipment indicated a detection "sweet spot" between 30 and 40 feet, though detection went out further [12]. The camera has a horizontal field of view of approximately 40 degrees, and a vertical field of view of approximately 30 degrees. The system processes images at 15 frames per second. The system algorithm assigns a detection confidence rating to the pavement markings on either side of the vehicle. The detection confidence rating is an integer between 0 and 3, with 3 being the highest confidence. The system requires a confidence value of 2 or greater in order to provide LDW assistance. Pavement markings that resulted in detection confidence ratings of 2 or higher were considered adequate for this study. Mobileye literature indicates the system cannot see better than the driver.

The device setup in each vehicle required slightly different approaches to extracting the detection confidence rating assigned to each longitudinal pavement marking. The data extraction process for each system is described in the following section.

Figure 4. Mobileye Camera from Exterior and Interior of Ford Explorer

Researchers attempted to acquire other MV systems for testing. The attempts were unsuccessful in terms of obtaining equipment with the necessary functionality to allow the researchers to determine the confidence level that the MV system had in detecting the markings. The Mobileye system tested was by far the most common system on the market when the project started. At the time of writing this report newer versions of the Mobileye system have been released that use newer hardware and software.

Data Acquisition System

In the Explorer, the MV system output was integrated into PolySync, a data logging system that simultaneously presents a graphical representation of the lane model developed by the MV system, the detection confidence rating overlaid on a forward viewing camera image, and other streaming data output from the MV system.

The goal of the data reduction process was to develop a database that would consider each time one of the vehicles passed by a longitudinal pavement marking as a unique observation. For observations made using the Explorer, screen capture video (see Figure 5) of the data collection software was manually reviewed. The researcher reviewing the video identified the most prevalent detection confidence rating for the first half and second half of each observation of the longitudinal pavement marking. These two values were then averaged to determine an overall average rating for the observation.

In the F-150, automated software was used to extract detection confidence ratings at a frequency of 10 hertz over the duration of the data collection. The automated data logging software associated with the MV of the F-150 created a spreadsheet output and uploaded via cellular connection to a data cloud for remote download, which eliminated the human aspect present in the data collected using the Explorer. Using GPS points, the beginning and end of each marking section were identified in the output. The data between the beginning and end of a particular marking were then averaged over the first half and second half of the marking, and then the two halves were averaged to create an overall detection confidence rating for the marking.

After the detection confidence ratings were extracted from each of the MV systems, they were then matched with field measurements of the pavement marking performance characteristics obtained using the CCD luminance camera and the other pavement marking performance characterization equipment as described in the following subsections.

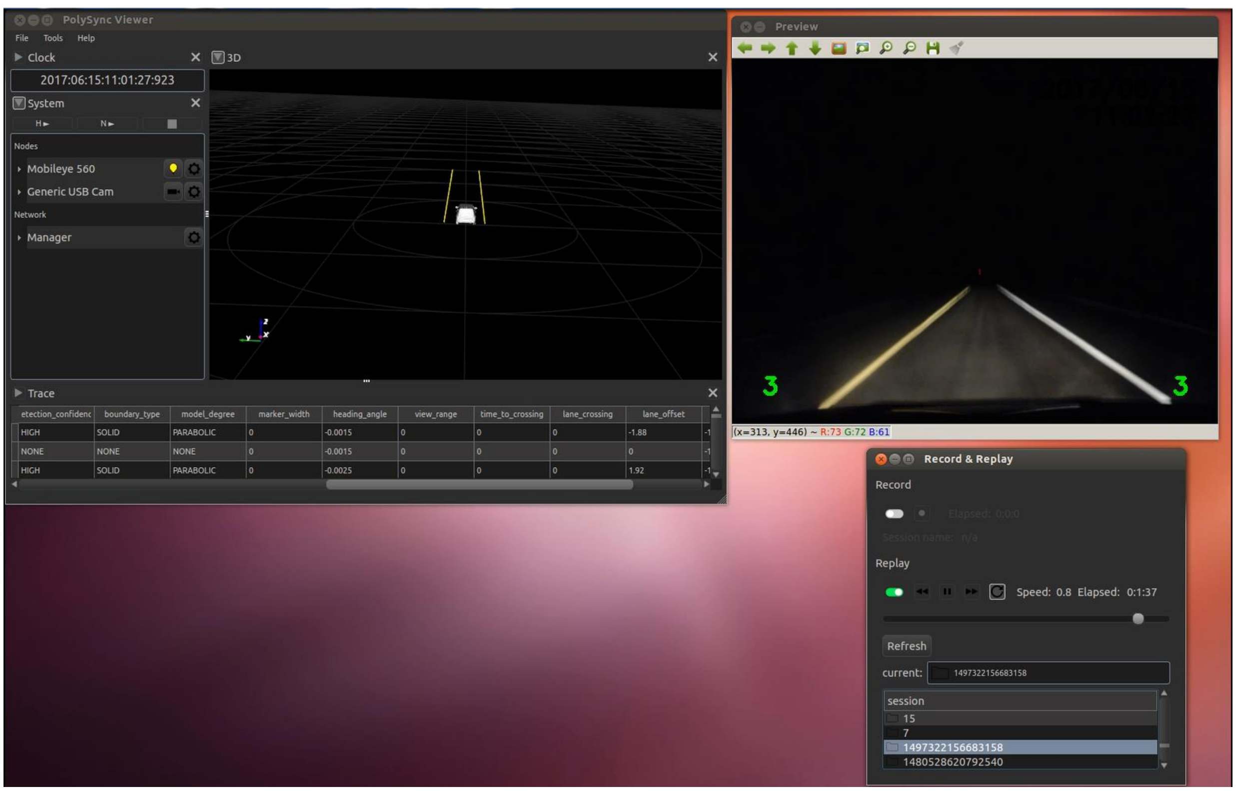


Figure 5. PolySync Screen Used for Data Reduction

Pavement Marking Color and Retroreflectivity Characterization

Delta LTL-XL Mark II and Delta LTL-XL handheld retroreflectometers were used to obtain measurements of coefficient of retroreflected luminance (R_L), which is indicative of visibility at night, and the luminance coefficient under diffuse illumination (Qd), which is indicative of visibility during the day. The retroreflectometers were used to evaluate each marking and the adjacent pavement at 20 foot intervals along the length of the markings in both directions. The recovery retroreflectivity, which measures the coefficient of retroreflected luminance of a pavement marking after it has been wetted, was also captured using the handheld retroreflectometer following ASTM E2177. Recovery retroreflectivity readings were conducted at 3 locations along each marking. A HunterLab MiniScan XE Plus portable spectrophotometer was used to obtain color (x, y chromaticity coordinates) and luminance (CIE Y) of the markings and pavements. This device measures data in the CIE color space. Measurements were collected using a two degree standard observer and illuminant D65. Color measurements were conducted at 5 locations along each marking. For all measurements the adjacent road surface was also evaluated.

CCD Luminance Camera

A CCD luminance camera (imaging colorimeter) was used to measure the luminance (L_v) of the markings under various lighting and wetting conditions. The camera, a Prometric I29, was mounted inside the Explorer near the MV system and captured information at four distances in front of the vehicle. The geometry of the evaluation was not a standard geometry but rather a field geometry representing the geometry at which the MV system was viewing the markings. To provide a frame of reference for each of the three nearest ranges, a ceramic Spectralon tile was placed adjacent to the location of the measurement. Figure 6 provides a screenshot of the CCD output. The output provides luminance and color information for the pavement markings and the surrounding pavement.

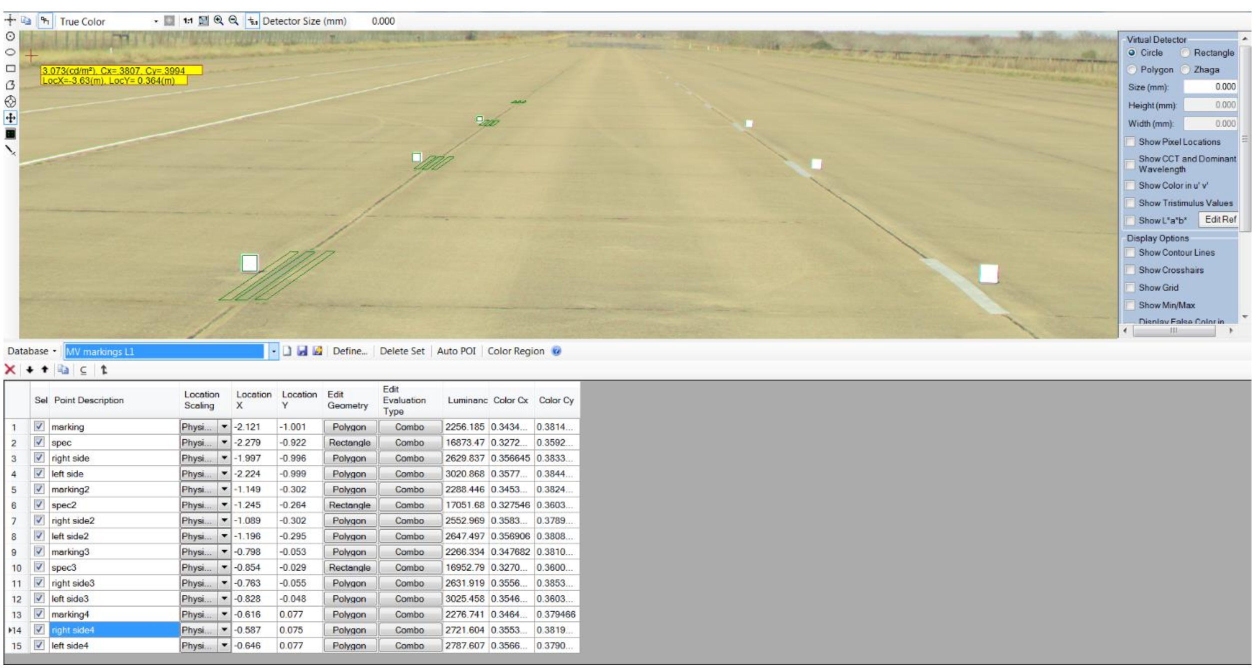


Figure 6. CCD Camera Output

A series of boxes are shown in green on the left side of Figure 6. These boxes identify the locations where the CCD image was being analyzed. The measurement locations were at 45, 85, 125, and 165 ft away from the measurement device, with each box being 10 ft long and centered at the aforementioned distances. Ultimately, the measurements taken at the 45-ft distance were used in the analysis since they were generally reflective of the area of interest being used by the MV system.

PAVEMENT MARKING SAMPLES

Eight longitudinal preformed tape pavement markings were examined during this study. Each marking was a preformed pavement marking tape provided by the 3M Company. The specific tapes included in this study were selected based on preliminary results of Phase I data collection for NCHRP 20-102 (06). An initial assessment of the detectability of the preformed tape pavement markings following the conclusion of the Phase I data collection period indicated that not every marking would need to be evaluated in the 4- vs. 6-inch comparison due to similar detection levels. This study primarily relies on data collected in parallel with Phase II of NCHRP 20-102 (06). Of the eight markings examined, five were evaluated at two different widths during Phase II (4 and 6 inches), while the remaining tape markings were evaluated only at 6 inches during Phase II and subsequently rely on data from Phase I to compare 4 and 6 inch markings. The longitudinal preformed tape pavement markings were installed in pairs such that the two different tape markings were observed simultaneously (i.e., one on either side of the vehicle).

The pavement marking tape was produced with specific color and retroreflectivity properties to cover a wide range of pavement marking quality to simulate varying levels of wear. The quantity of optics and quality of the pigments were modified by the manufacturer to produce markings that have performance similar to that of aged markings. The majority of the tape had the standard profiled tape pattern, but some of the tape was flat due to the modifications to simulate wearing of the product. The markings were not all of uniform color. Some markings had discolored profile bumps while the remaining base material was of standard color. This resulted in the markings having different color appearance at different viewing distances.

During Phase I, the markings were evaluated as broken lane line markings and continuous edge line markings, but for Phase II, only the continuous edge line pavement markings were examined. Initial Phase I analysis between the broken lane line markings and continuous edge line markings showed little difference in detectability by the MV system. Subsequently, this study focuses on continuous markings as no observations were taken of broken 6-inch lane line markings. The marking samples and the width that they were installed during each data collection period are summarized in Table 1 (the side field indicates the side of the lane on which the marking was installed relative to northbound travel). Samples WT1, WT7, YT2, YT3, and YT4 were observed as both 4- and 6-inch markings during the Phase II data collection period. This was accomplished by first installing a 4-inch marking, and then adding a 2-inch marking immediately adjacent to those markings to make a 6-inch marking. The samples evaluated as 4-inch markings during the Phase I data collection had performance characteristics similar to those evaluated during Phase II. An example pavement marking showing both the 4- and additional 2-inch strip is provided in Figure 7.

Figure 7. Example 4- and 2-inch Sections of the Preformed Tape Pavement Marking

The Phase II data collection focused on continuous longitudinal preformed tape pavement markings of similar material but of 4- and 6-inch widths. Each of the samples possess various characteristics that affect their visibility to the human eye and MV systems. The research aimed to control marking quality in the assessment of marking width on detectability by MV systems.

Table 1. Summary of Sample Location and Width

				Phase I Data Collection			Phase II Data Collection		
Sample	**Material**	**Color**	**Structure**	**Section**	**Side**	**Width (in.)**	**Section**	**Side**	**Width (in.)**
WT1	Tape	White	Profiled	6	Right	4	4	Right	4, 6
WT3	Tape	White	Flat	7	Left	4	3	Right	6
WT6	Tape	White	Profiled	1	Right	4	1	Right	6
WT7	Tape	White	Profiled	4	Right	4	2	Right	4, 6
YT1	Tape	Yellow	Flat	1	Left	4	1	Left	6
YT2	Tape	Yellow	Profiled	6	Left	4	4	Left	4, 6
YT3	Tape	Yellow	Profiled	3	Left	4	2	Left	4, 6
YT4	Tape	Yellow	Profiled	5	Left	4	3	Left	4, 6

Table 2 summarizes the lengths of the longitudinal pavement markings used and the spacing between the marking sections. The markings are relatively consistent in length within each phase of data collection, with the exception of sample WT3 during Phase I. Similarly, the spacing between each of the markings is also similar within each phase of research. The most notable difference between the two phases is in the spacing, which was much smaller during Phase I.

Table 2. Marking Lengths and Separation Distances

	Phase I Data Collection			Phase II Data Collection		
Marking Label	Distance from Previous Marking	Marking Length	Distance to Next Marking	Distance from Previous Marking	Marking Length	Distance to Next Marking

WT1	130	410	130	785	420	NA
WT3	130	250	NA	685	355	785
WT6	NA	490	190	NA	400	660
WT7	130	450	150	660	395	685
YT1	NA	490	190	NA	315	785
YT2	130	410	130	725	380	NA
YT3	170	410	130	785	410	670
YT4	150	410	130	670	415	725

PAVEMENT MARKING PROPERTIES

The performance characteristics for each of the marking samples were observed in each of the data collection periods. The following sections document the properties of each sample and the adjacent pavement surface in each of the two data collection periods. Several of the measurements were taken for each direction of travel to account for conditions when the directionality of the marking or observation would influence the performance. The following sections provides a graphical summary of the properties collected during this study. Appendix A provides tabular summaries of the various marking properties. Appendix B provides images of the pavement markings and the pavement marking layout.

Daytime Conditions

Figure 8 illustrates the luminance (CIE Y) measurements taken during both data collection periods. The value for Y is a scaled value between 0 and 100, with 0 representing a perfect black and 100 representing a perfect white. The brighter (whiter) a marking is the higher the luminance it will have. As indicated in the previous section, the markings were modified from the standard markings to simulate wear. Subsequently, the coloring of the markings is not uniform. The non-uniformity is reflected in the fact that the valleys between the raised portions of the profiled tape markings are brighter than the elevated portions. Due to this uneven wearing, the measured Y value may not correlate directly to the Y value observed by MV system.

Figure 9 contains the Qd measurements collected during daytime conditions. The value of Qd has a range similar to R_L and has the same measurement units. Qd is a comparable daytime (or at night under overhead illumination) measurement to the nighttime R_L measurement. In general, the differences between the magnitude of the Qd measurements between samples is on par with the magnitude of the differences of the CIE Y measurements, with some exceptions.

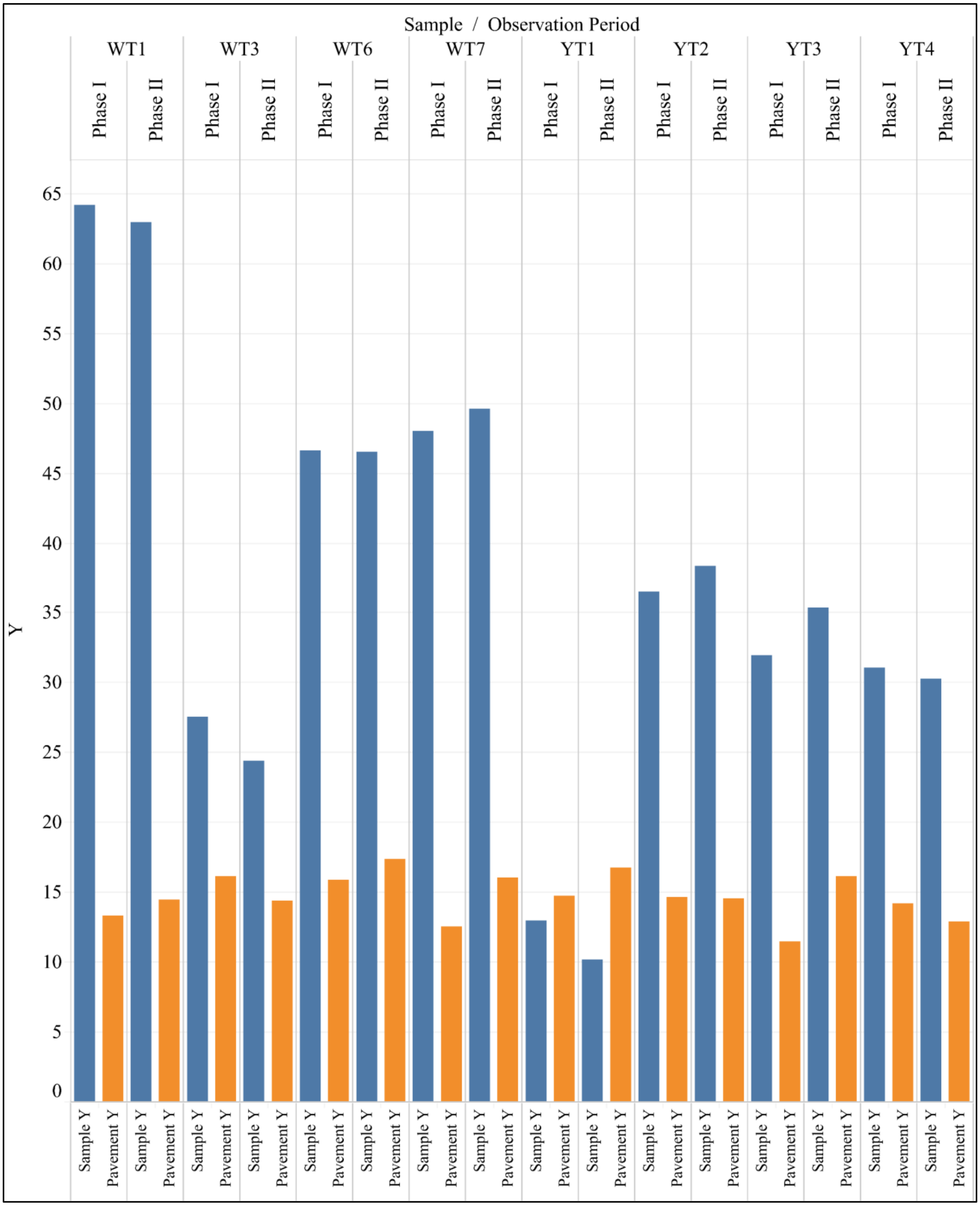


Figure 8. Y Measurements During Dry, Daytime Conditions

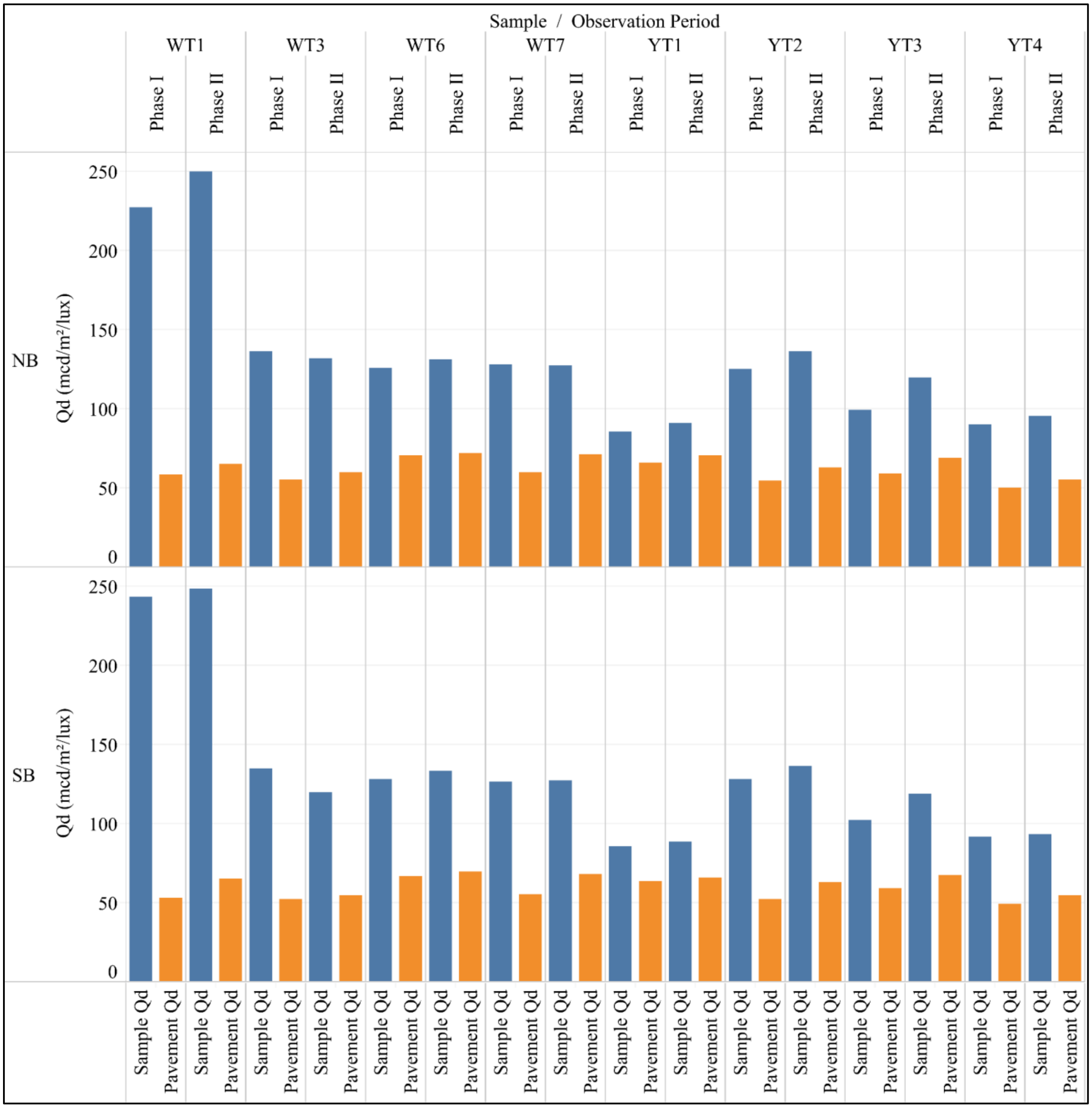


Figure 9. Retroreflectometer Qd Measurements

Figure 10 contains the values for the CCD luminance under dry, daytime conditions that were collected during both data collection periods. The observed values for both the markings and pavement are higher during the Phase II data collection period.

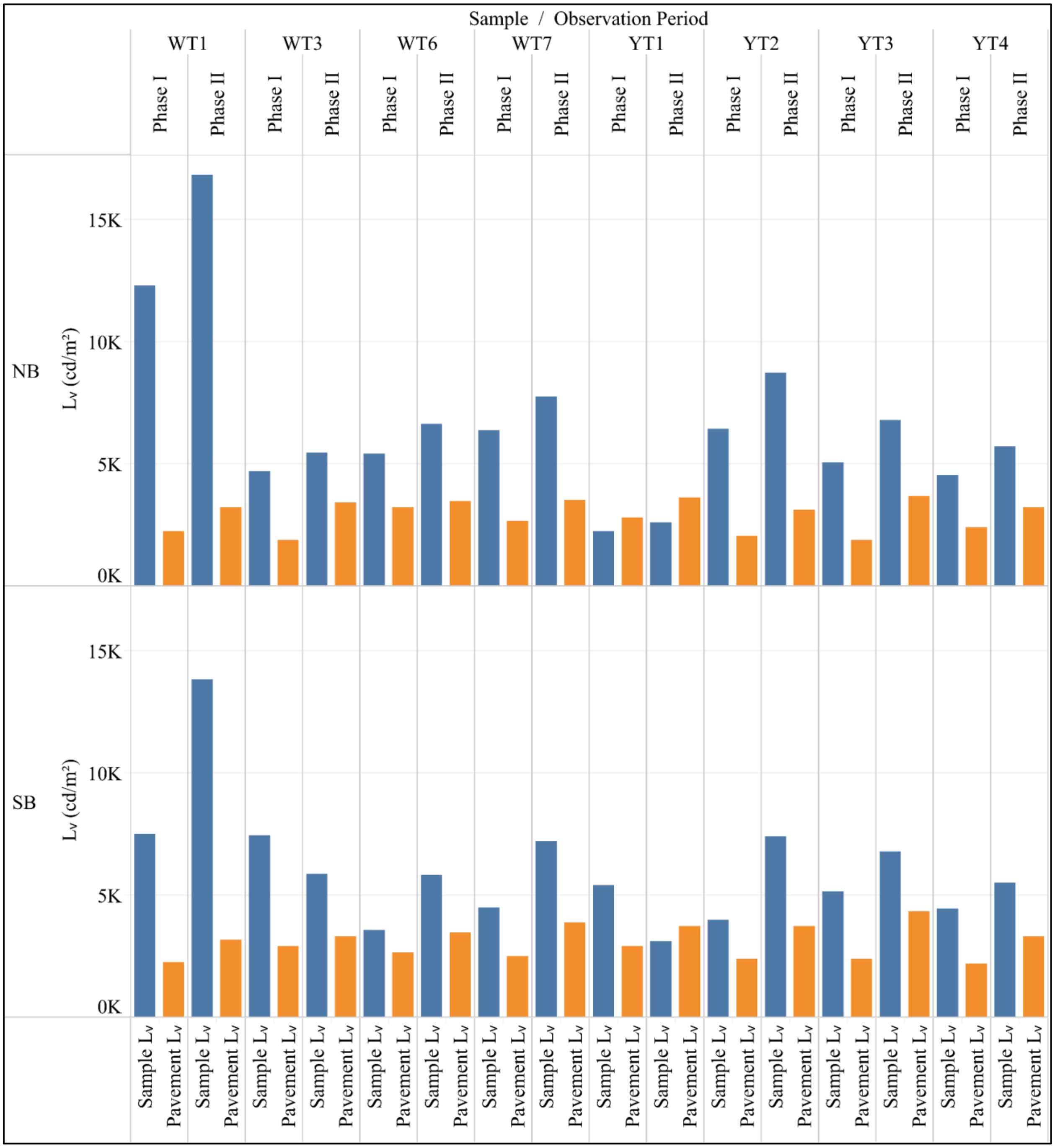
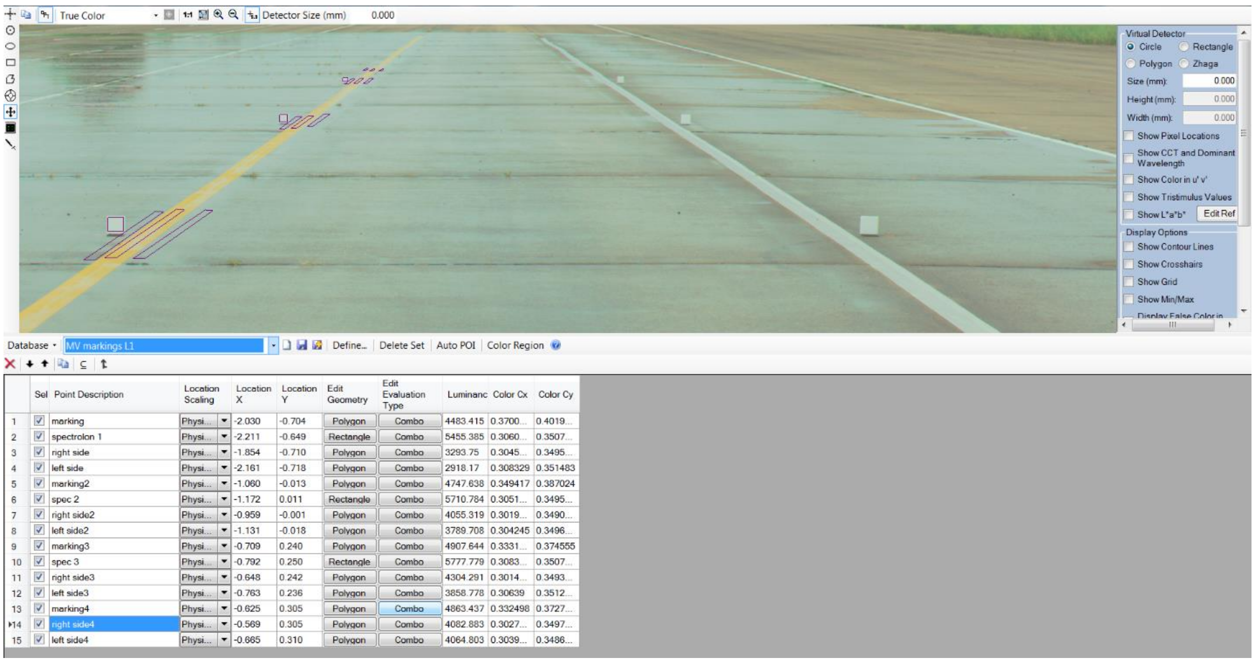


Figure 10. CCD Luminance During Dry, Daytime Conditions

The visibility characteristics observed by the CCD camera are dependent on the amount of light falling on the sample (illuminance), the geometry of the light source, and the geometry of the camera in relation to the target. The presence of water on the markings and pavement surface affects the way that light is reflected, and subsequently, results in different measurement of illuminance, hence, it was necessary to capture separate measurements under wet conditions. Figure 11 illustrates the CCD camera display during wet, daytime data collection. Dry pavement can be seen in the upper-right corner of the image providing a visual comparison of how the pavement markings contrast with the pavement under wet and dry conditions.



	Sel	Point Description	Location Scaling	Location X	Location Y	Edit Geometry	Edit Evaluation Type	Luminanc	Color Cx	Color Cy
1	☑	marking	Physi...	-2.030	-0.704	Polygon	Combo	4483.415	0.3700...	0.4019...
2	☑	spectrolon 1	Physi...	-2.211	-0.649	Rectangle	Combo	5455.385	0.3060...	0.3507...
3	☑	right side	Physi...	-1.854	-0.710	Polygon	Combo	3293.75	0.3045...	0.3495...
4	☑	left side	Physi...	-2.161	-0.718	Polygon	Combo	2918.17	0.308329	0.351483
5	☑	marking2	Physi...	-1.060	-0.013	Polygon	Combo	4747.638	0.349417	0.387024
6	☑	spec 2	Physi...	-1.172	0.011	Rectangle	Combo	5710.784	0.3051...	0.3495...
7	☑	right side2	Physi...	-0.959	-0.001	Polygon	Combo	4055.319	0.3019...	0.3490...
8	☑	left side2	Physi...	-1.131	-0.018	Polygon	Combo	3789.708	0.304245	0.3496...
9	☑	marking3	Physi...	-0.709	0.240	Polygon	Combo	4907.644	0.3331...	0.374555
10	☑	spec 3	Physi...	-0.792	0.250	Rectangle	Combo	5777.779	0.3083...	0.3507...
11	☑	right side3	Physi...	-0.648	0.242	Polygon	Combo	4304.291	0.3014...	0.3493...
12	☑	left side3	Physi...	-0.763	0.236	Polygon	Combo	3858.778	0.30639	0.3512...
13	☑	marking4	Physi...	-0.625	0.305	Polygon	Combo	4863.437	0.332498	0.3727...
▸14	☑	right side4	Physi...	-0.569	0.305	Polygon	Combo	4082.883	0.3027...	0.3497...
15	☑	left side4	Physi...	-0.665	0.310	Polygon	Combo	4064.803	0.3039...	0.3486...

Figure 11. Wet, Daytime CCD Image

Figure 12 documents CCD observations during wet, daytime conditions. The figure illustrates that the values obtained for these measurements were dependent on the lighting conditions present at the time, as the values are typically higher in during the Phase II data collection period.

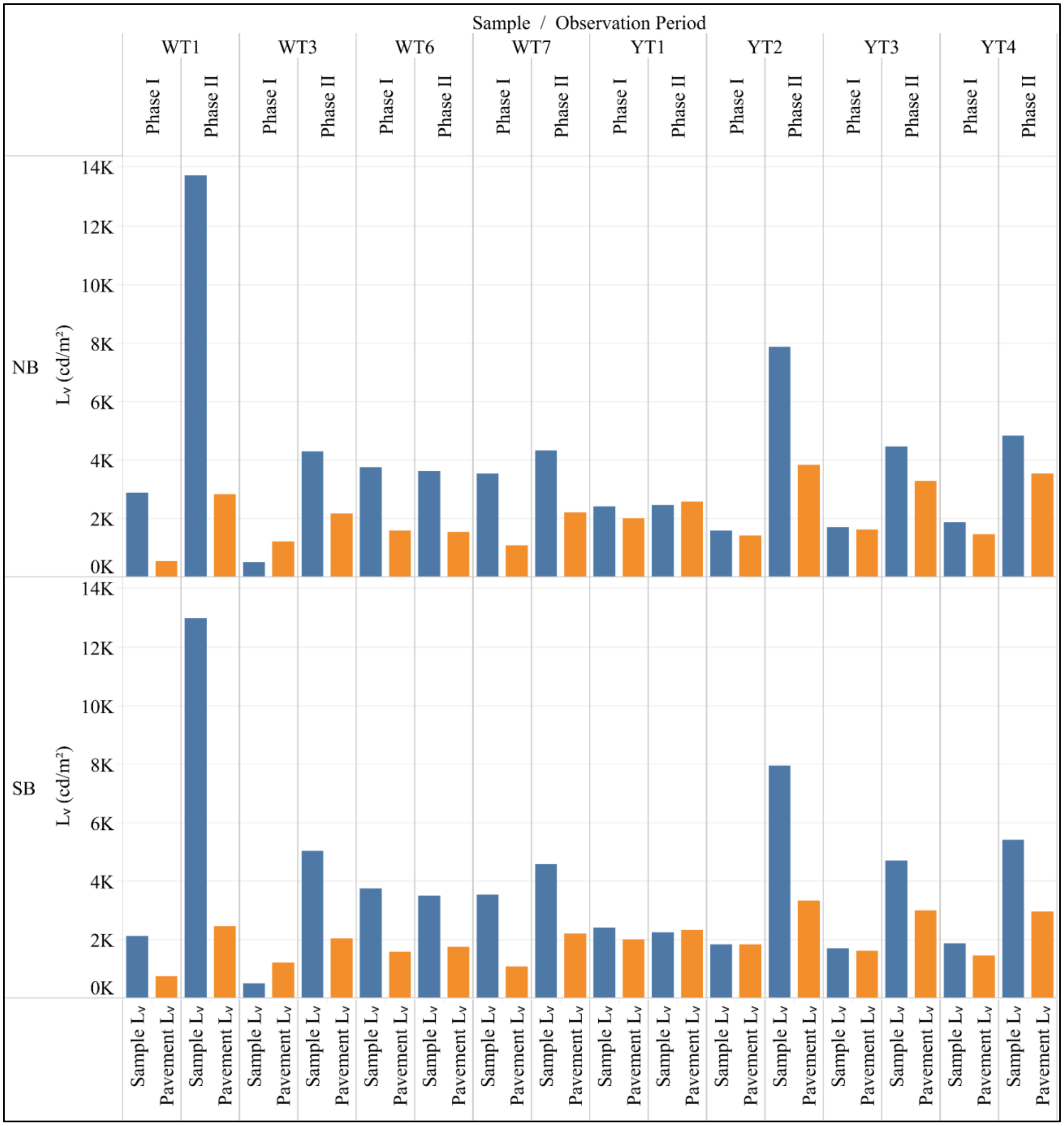


Figure 12. CCD Luminance Measurements During Wet, Daytime Conditions

Nighttime Conditions

Sample characteristics such as CIE Y and Qd are generally applicable during daytime conditions. The ability of both humans and cameras to detect pavement markings at night is better characterized by the coefficient of retroreflected luminance (R_L), commonly referred to as the markings retroreflectivity. Subsequently, Figure 13 documents the retroreflectivity measurements for each of the samples during both Phase I and Phase II of data collection.

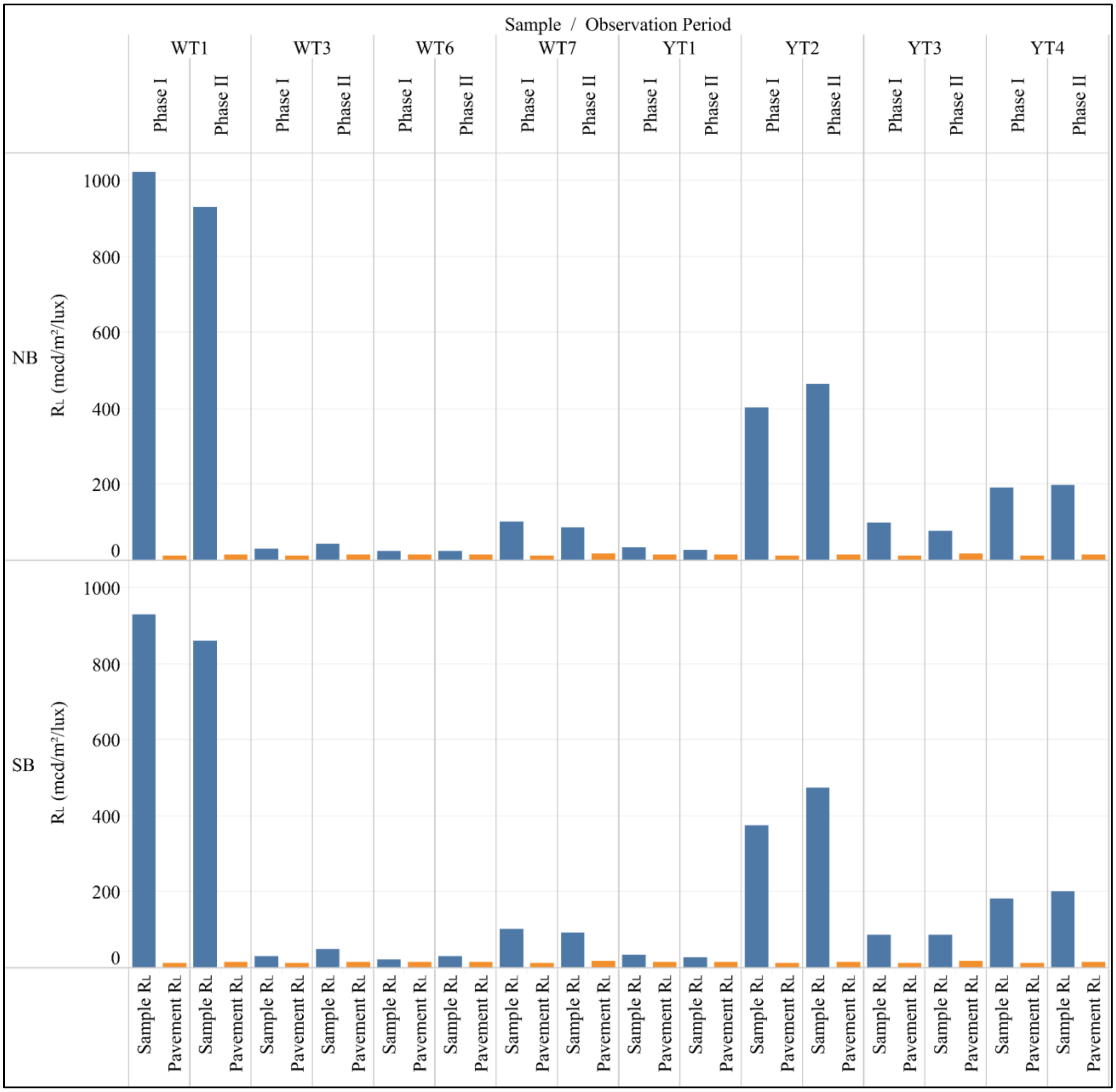


Figure 13. Marking Retroreflectivity

Figure 14 presents the measurements for the wet recovery retroreflectivity, which captures the retroreflectivity of the pavement marking while recovering after being wetted. Generally speaking, these values were higher during Phase II of the data collection, with the most pronounced difference for sample A. Samples YT2 and YT4 showed slightly lower values during Phase II of the data collection. The wet recovery retroreflectivity of the pavement was 2 mcd/m^2/lux for all test areas. Wet recovery values were used to assess the effectiveness of the pavement markings under wet pavement conditions.

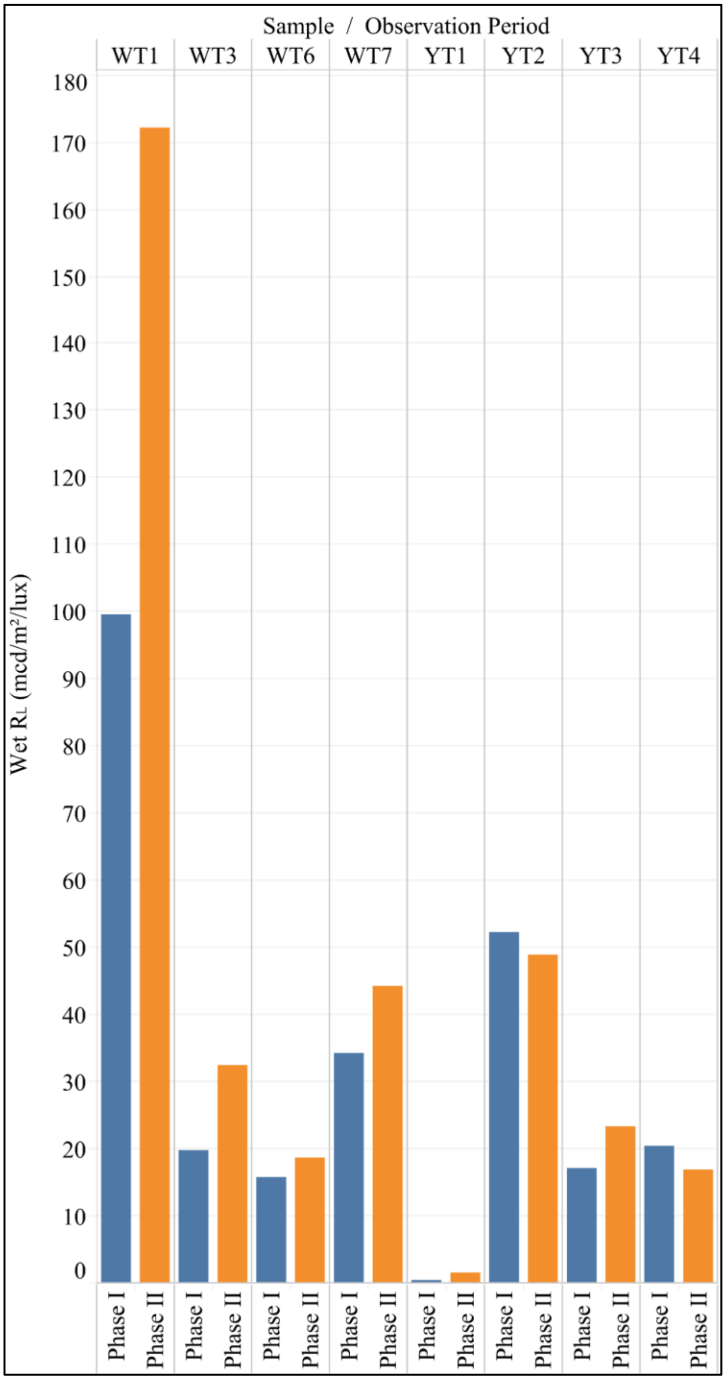
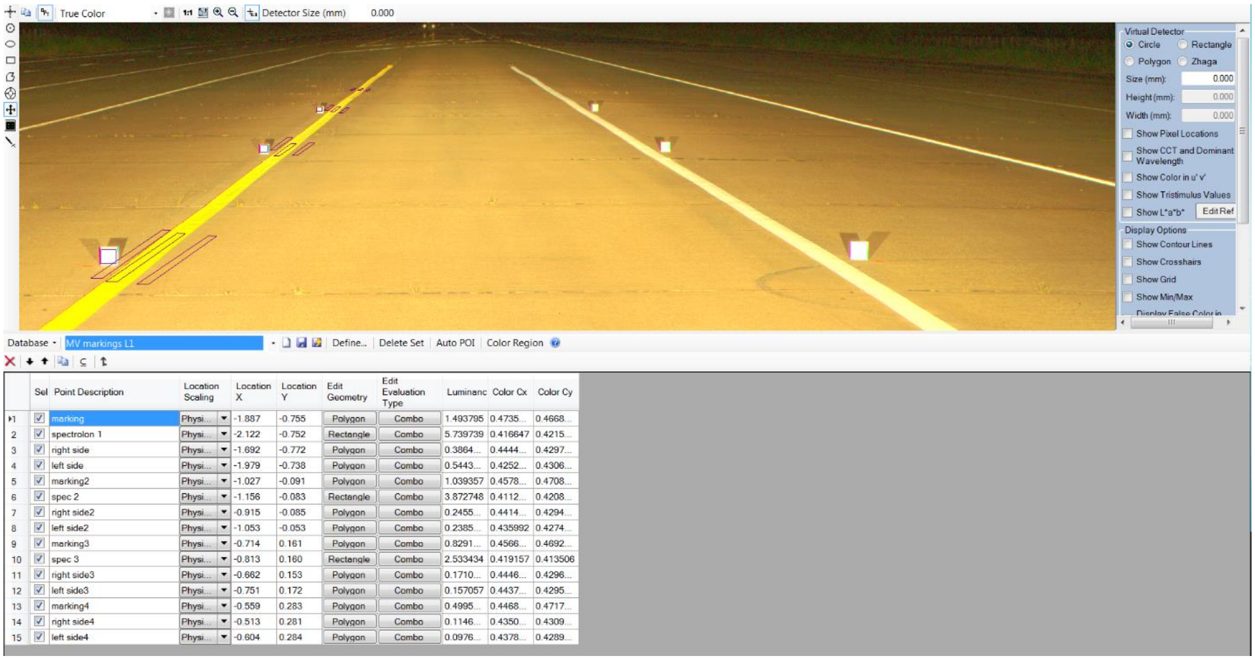


Figure 14. Marking Recovery Retroreflectivity

The visibility characteristics observed by the CCD camera are dependent on the amount of light falling on the sample (illuminance), the geometry of the light source, and the geometry of the camera in relation to the target. Figure 15 illustrates the CCD display during dry, nighttime data collection and how the light source is restricted to the vehicle headlights. Figure 16 contains the measurements of CCD luminance that were collected during dry, nighttime conditions. As expected these measurements are relatively consistent across data collection periods given that only the headlights of the data collection vehicle (Explorer) are impacting the measurements.



	Sel	Point Description	Location Scaling	Location X	Location Y	Edit Geometry	Edit Evaluation Type	Luminanc	Color Cx	Color Cy
1	☑	marking	Physi...	-1.887	-0.755	Polygon	Combo	1.493795	0.4735...	0.4668...
2	☑	spectrolon 1	Physi...	-2.122	-0.752	Rectangle	Combo	5.739739	0.416647	0.4215...
3	☑	right side	Physi...	-1.692	-0.772	Polygon	Combo	0.3864...	0.4444...	0.4297...
4	☑	left side	Physi...	-1.979	-0.738	Polygon	Combo	0.5443...	0.4252...	0.4306...
5	☑	marking2	Physi...	-1.027	-0.091	Polygon	Combo	1.039357	0.4578...	0.4708...
6	☑	spec 2	Physi...	-1.156	-0.083	Rectangle	Combo	3.872748	0.4112...	0.4208...
7	☑	right side2	Physi...	-0.915	-0.085	Polygon	Combo	0.2455...	0.4414...	0.4294...
8	☑	left side2	Physi...	-1.053	-0.053	Polygon	Combo	0.2385...	0.435992	0.4274...
9	☑	marking3	Physi...	-0.714	0.161	Polygon	Combo	0.8291...	0.4566...	0.4692...
10	☑	spec 3	Physi...	-0.813	0.160	Rectangle	Combo	2.533434	0.419157	0.413506
11	☑	right side3	Physi...	-0.662	0.153	Polygon	Combo	0.1710...	0.4446...	0.4296...
12	☑	left side3	Physi...	-0.751	0.172	Polygon	Combo	0.157057	0.4437...	0.4295...
13	☑	marking4	Physi...	-0.559	0.283	Polygon	Combo	0.4995...	0.4468...	0.4717...
14	☑	right side4	Physi...	-0.513	0.281	Polygon	Combo	0.1146...	0.4350...	0.4309...
15	☑	left side4	Physi...	-0.604	0.284	Polygon	Combo	0.0976...	0.4378...	0.4289...

Figure 15. CCD Camera Display During Dry, Nighttime Data Collection

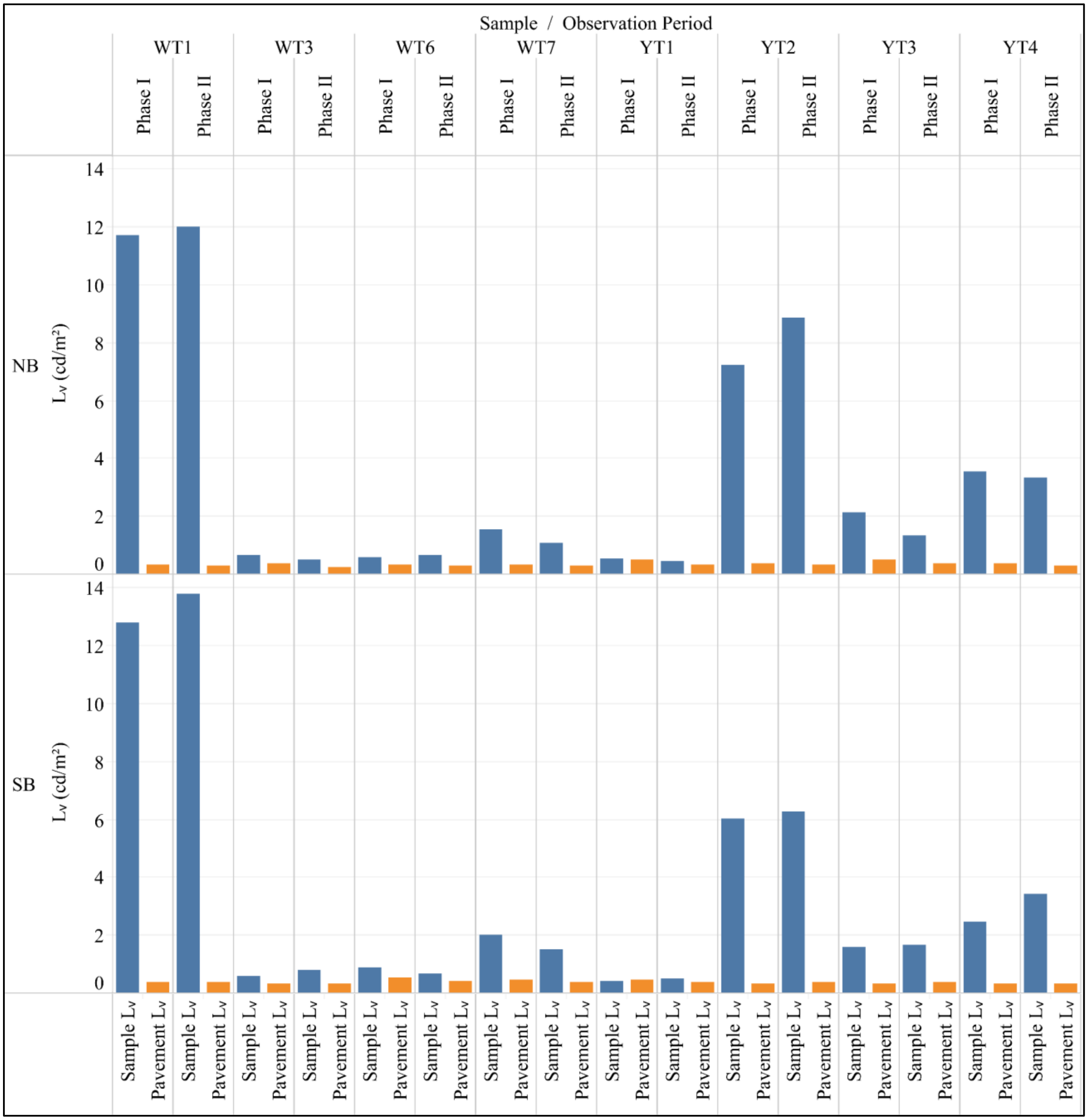
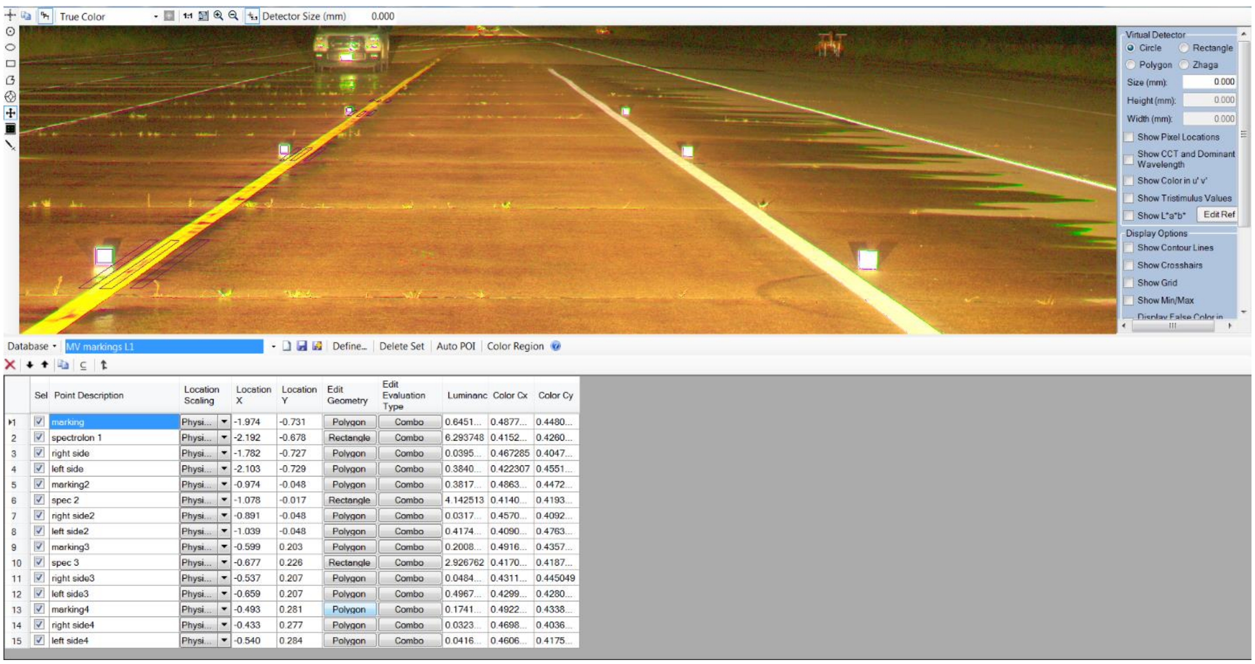


Figure 16. CCD Luminance Measurements During Dry, Nighttime Conditions

There are large discrepancies between the observed luminance values from the daytime and nighttime CCD observations. This is due to the aforementioned fact that the luminance values are dependent on the amount of light (both in terms of intensity and angle) hitting the sample. Subsequently, the observations that occurred at night are substantially lower, as only the vehicle headlights were providing the illumination.

Figure 17 illustrates the CCD interface during wet, nighttime data collection. In the upper-right corner of the camera view shown in Figure 17, the pavement is dry, while the remainder of the pavement shown is wet. This figure helps demonstrate the effect of moisture on pavement color, and subsequently, on the contrast between the pavement marking and the pavement. In the upper-left portion, a vehicle can be observed. During this portion of the data collection activities, the vehicle had no lights on and the vehicle is merely in position for the glare portion of the study. Figure 18 illustrates the observations of the CCD luminance captured during Phase II wet, nighttime conditions. Relative to the observations taken during the daytime, these values are substantially lower, as the lighting is due to the headlights of the observation vehicle as opposed to the sun. Wet CCD measurements were not taken during Phase I because the CCD camera was under repair.



	Sel	Point Description	Location Scaling	Location X	Location Y	Edit Geometry	Edit Evaluation Type	Luminanc	Color Cx	Color Cy
1	☑	marking	Physi...	-1.974	-0.731	Polygon	Combo	0.6451...	0.4877...	0.4480...
2	☑	spectrolon 1	Physi...	-2.192	-0.678	Rectangle	Combo	6.293748	0.4152...	0.4260...
3	☑	right side	Physi...	-1.782	-0.727	Polygon	Combo	0.0395...	0.467285	0.4047...
4	☑	left side	Physi...	-2.103	-0.729	Polygon	Combo	0.3840...	0.422307	0.4551...
5	☑	marking2	Physi...	-0.974	-0.048	Polygon	Combo	0.3817...	0.4863...	0.4472...
6	☑	spec 2	Physi...	-1.078	-0.017	Rectangle	Combo	4.142513	0.4140...	0.4193...
7	☑	right side2	Physi...	-0.891	-0.048	Polygon	Combo	0.0317...	0.4570...	0.4092...
8	☑	left side2	Physi...	-1.039	-0.048	Polygon	Combo	0.4174...	0.4090...	0.4763...
9	☑	marking3	Physi...	-0.599	0.203	Polygon	Combo	0.2008...	0.4916...	0.4357...
10	☑	spec 3	Physi...	-0.677	0.226	Rectangle	Combo	2.926762	0.4170...	0.4187...
11	☑	right side3	Physi...	-0.537	0.207	Polygon	Combo	0.0484...	0.4311...	0.445049
12	☑	left side3	Physi...	-0.659	0.207	Polygon	Combo	0.4967...	0.4299...	0.4280...
13	☑	marking4	Physi...	-0.493	0.281	Polygon	Combo	0.1741...	0.4922...	0.4338...
14	☑	right side4	Physi...	-0.433	0.277	Polygon	Combo	0.0323...	0.4698...	0.4036...
15	☑	left side4	Physi...	-0.540	0.284	Polygon	Combo	0.0416...	0.4606...	0.4175...

Figure 17. CCD Camera Interface During Wet, Nighttime Data Collection

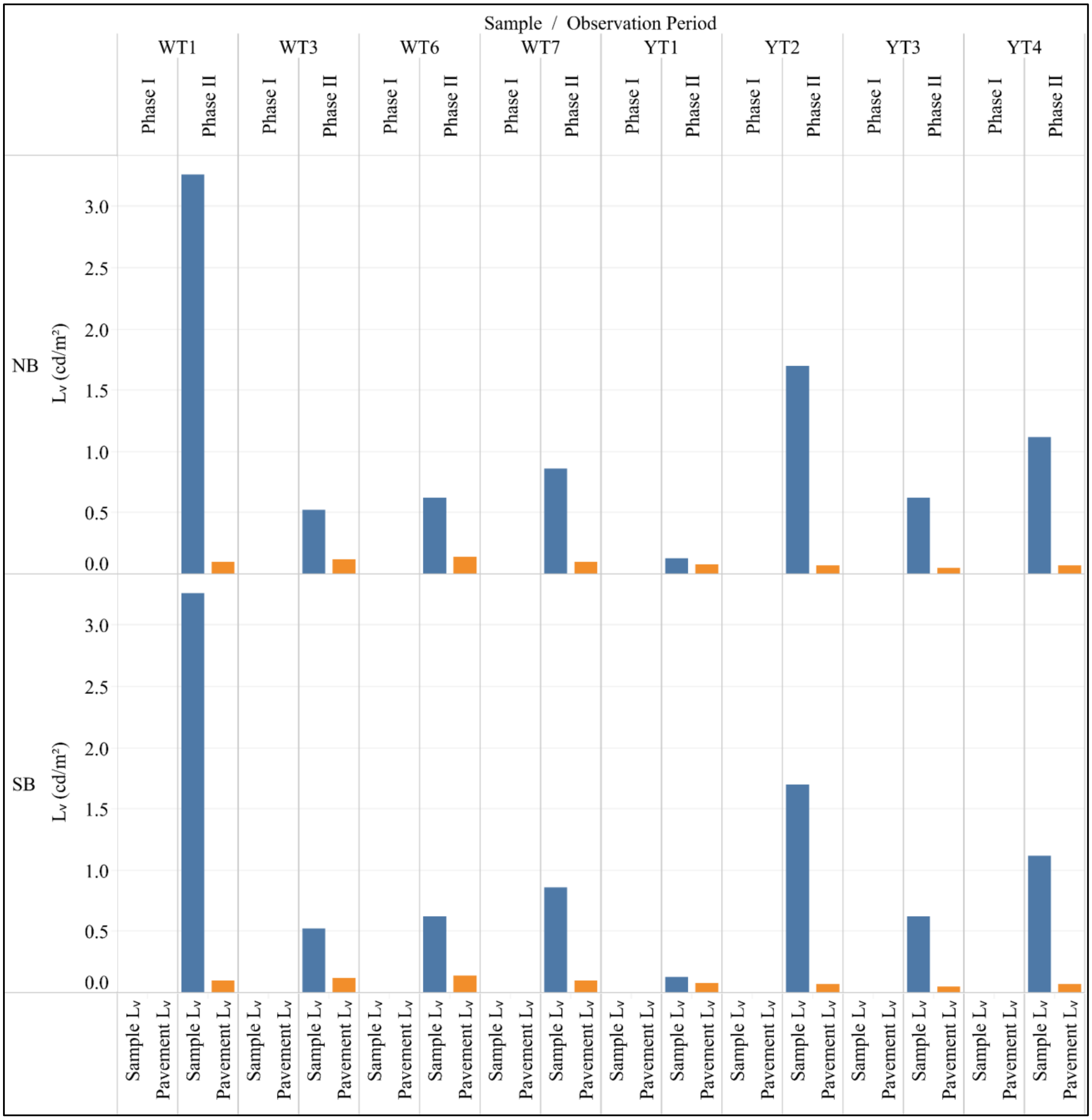


Figure 18. Phase II CCD Luminance During Wet, Nighttime Conditions

Nighttime Glare Conditions

During the Phase II data collection period, measurements were taken at night in the presence of glare applied by the headlights of a stationary vehicle located to simulate oncoming traffic under both dry and wet pavement conditions. Figure 19 illustrates the user interface of the CCD camera during dry, nighttime, data collection with glare applied from an opposing vehicle's headlights. Figure 19 demonstrates what is generally observed by any human driver of an automobile at night, the vision-inhibiting glare of the headlights of an oncoming vehicle.

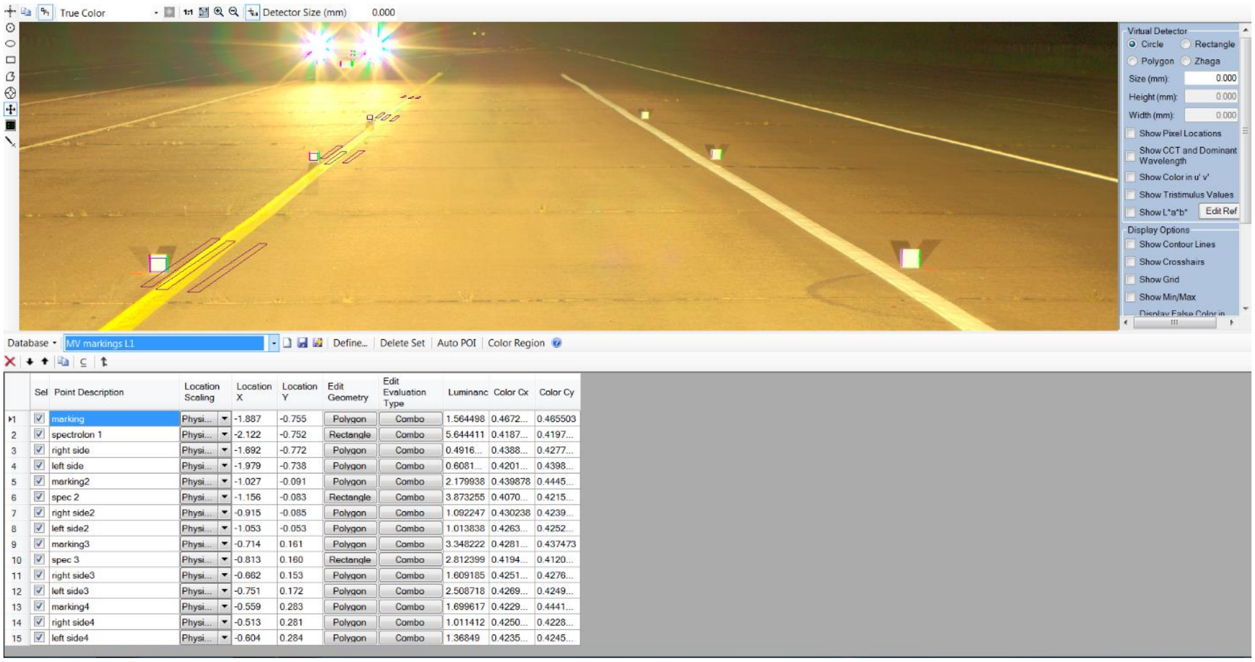


Figure 19. CCD Interface During Dry, Nighttime, Glare Data Collection

Figure 20 illustrates the interface of the CCD camera during wet, nighttime data collection with glare applied by oncoming headlights. The effect of headlights illustrated in Figure 19 is also noticeable in Figure 20. The effect appears to be potentially enhanced by the additional reflection due to water on the roadway. Figure 21 is split into two parts: the top illustrates the CCD luminance during dry, nighttime conditions with glare applied using another vehicle's headlights, while the bottom presents the data CCD luminance under the same scenario except with wet pavement.

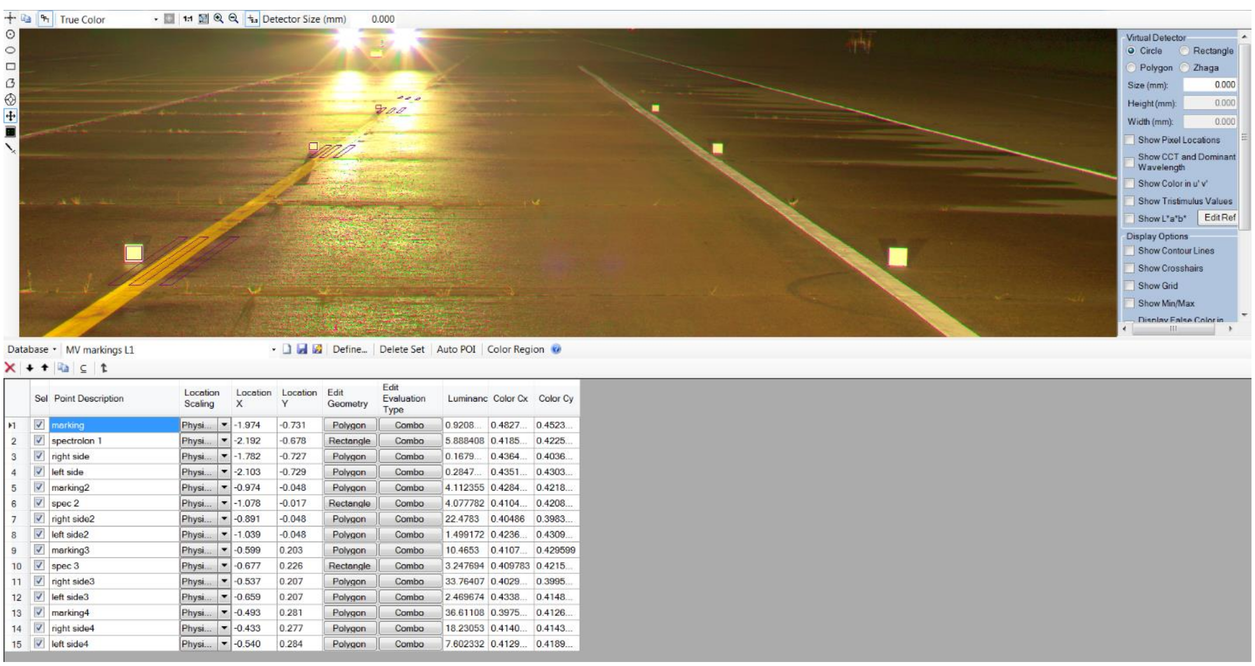


Figure 20. CCD Interface During Wet, Glare, Nighttime Data Collection

Figure 21. CCD Luminance During Dry and Wet Nighttime Conditions with Glare

The glare condition testing was not included in the scope of the project. Researchers added it to see potential impacts and to generate some initial data to help influence future research. Observations of CCD MV geometry luminance were not collected for samples WT1, YT2, YT4, and WT3 during nighttime, dry, glare conditions due to time constraints. Of the samples that were observed under dry, glare conditions, the values obtained for wet, glare conditions were fairly comparable, with samples YT1 and YT3 having slightly lower observations. As previously indicated the luminance values used were at the 45 foot distance. This distance did not fall directly in the glare path of the static evaluation.

CHAPTER 3. DATA COLLECTION AND ANALYSIS

MV DATA COLLECTION

This analysis investigated eight profiled tape markings with varying properties to assess any detection differences between 4-inch and 6-inch wide preformed tape pavement markings by an MV-based ADAS. Due to constraints on sample availability, three of the markings (denoted YT1, WT3, and WT6) were only observed as 4-inch markings during the Phase I data collection period, and 6-inch markings during Phase II of the data collection. Due to differences in sun position between the Phase I and Phase II data collection periods, care must be taken when drawing conclusions about the daytime visibility of these markings.

Table 3. Disaggregate Count of Dry, Daytime Observations

Cloud Cover	**No Clouds**				**Some clouds**		**Clouds**				
Speed (mph)	**50**		**65**		**65**		**50**		**65**		
Travel Direction	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**Total**
WT1	9	8	5	4	1	1	1	2	0	1	32
Phase I-4in	5	5	1	1	0	0	0	0	0	0	12
Phase II-4 in	2	1	3	2	0	0	1	2	0	1	12
Phase II- 6 in	2	2	1	1	1	1	0	0	0	0	8
WT3	6	6	4	4	1	1	1	1	1	1	26
Phase I-4 in	2	2	1	1	0	0	0	0	0	0	6
Phase II-6 in	4	4	3	3	1	1	1	1	1	1	20
WT6	8	6	4	7	0	0	2	3	2	0	32
Phase I-4 in	5	5	1	1	0	0	0	0	0	0	12
Phase II-6 in	3	1	3	6	0	0	2	3	2	0	20
WT7	8	8	5	5	0	0	2	2	1	1	32
Phase I-4 in	5	5	1	1	0	0	0	0	0	0	12
Phase II-4 in	2	2	3	2	0	0	1	1	0	1	12
Phase II-6 in	1	1	1	2	0	0	1	1	1	0	8
YT1	5	3	4	7	0	0	2	3	2	0	26
Phase I-4 in	2	2	1	1	0	0	0	0	0	0	6
Phase II-6 in	3	1	3	6	0	0	2	3	2	0	20
YT2	8	7	5	4	1	1	1	2	0	1	30
Phase I-4 in	4	4	1	1	0	0	0	0	0	0	10
Phase II-4 in	2	1	3	2	0	0	1	2	0	1	12
Phase II-6 in	2	2	1	1	1	1	0	0	0	0	8
YT3	7	7	5	5	0	0	2	2	1	1	30
Phase I-4 in	4	4	1	1	0	0	0	0	0	0	10
Phase II-4 in	2	2	3	2	0	0	1	1	0	1	12
Phase II-6 in	1	1	1	2	0	0	1	1	1	0	8
YT4	8	8	4	4	1	1	1	1	1	1	30
Phase I-4 in	4	4	1	1	0	0	0	0	0	0	10
Phase II-4 in	2	2	3	2	0	0	1	1	0	1	12
Phase II-6 in	2	2		1	1	1	0	0	1	0	8
Total	**59**	**53**	**36**	**40**	**4**	**4**	**12**	**16**	**8**	**6**	**238**

For each of the scenarios previously described in the report, each of the samples were observed multiple times using the Explorer and F-150. The following tables document the number of observations made for each of the various conditions, beginning with the dry, daytime observations using the Explorer shown in Table 3. Rather than simply showing the counts of observations by each sample and width combination, these counts are disaggregated based on cloud cover, speed, direction of travel, and the data collection phase.

Table 4 presents the count of observations taken using the Explorer in wet, daytime conditions. Observations were only taken at 50 mph.

Table 4. Disaggregate Count of Wet, Daytime Observations

Cloud Cover	**No Clouds**		**Some clouds**		**Clouds**		
Travel Direction	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**Total**
WT1	8	7	1	0	3	1	20
Phase I-4in	3	2	1	0	3	1	10
Phase II-4 in	2	3	0	0	0	0	5
Phase II- 6 in	3	2	0	0	0	0	5
WT3	5	5	0	0	1	0	11
Phase I-4 in	0	0	0	0	0	0	0
Phase II-6 in	5	5	0	0	1	0	11
WT6	9	2	2	1	6	2	22
Phase I-4 in	9	2	1	0	4	1	17
Phase II-6 in	0	0	1	1	2	1	5
WT7	9	5	3	1	3	1	22
Phase I-4 in	6	2	1	0	3	1	13
Phase II-4 in	0	1	2	1	0	0	4
Phase II-6 in	3	2	0	0	0	0	5
YT1	0	0	1	1	2	1	5
Phase I-4 in	0	0	0	0	0	0	0
Phase II-6 in	0	0	1	1	2	1	5
YT2	8	7	1	0	3	1	20
Phase I-4 in	3	2	1	0	3	1	10
Phase II-4 in	2	3	0	0	0	0	5
Phase II-6 in	3	2	0	0	0	0	5
YT3	10	5	3	1	4	1	24
Phase I-4 in	7	2	1	0	4	1	15
Phase II-4 in	0	1	2	1	0	0	4
Phase II-6 in	3	2	0	0	0	0	5
YT4	10	7	1	0	4	1	23
Phase I-4 in	5	2	1	0	3	1	12
Phase II-4 in	2	3	0	0	1	0	6
Phase II-6 in	3	2	0	0	0	0	5
Total	**59**	**38**	**12**	**4**	**26**	**8**	**147**

Table 5 presents the observations taken during nighttime conditions using the Explorer. This includes nighttime, dry observations (ND); nighttime, wet observations (NW); nighttime, dry, glare observations (NDG); and nighttime, wet, and glare (NWG) observations. During nighttime observations, cloud cover was not considered as the moon generally does not provide enough light to substantially illuminate the pavement markings. During wet and glare conditions, observations were only made at 50 mph. Finally, the glare observations were only made in the northbound direction of travel.

Table 5. Disaggregate Count of Nighttime Observations

	ND					NW			NDG	NWG
Speed (mph)	**50**		**65**			**50**			**50**	**50**
Travel Direction	**NB**	**SB**	**NB**	**SB**	**Total**	**NB**	**SB**	**Total**	**NB**	**NB**
WT1	6	6	5	5	22	10	6	16	3	3
Phase I-4in	2	2	1	1	6	4	2	6	0	0
Phase II-4 in	2	2	2	2	8	3	2	5	2	2
Phase II- 6 in	2	2	2	2	8	3	2	5	1	1
WT3	6	6	5	5	22	7	4	11	3	3
Phase I-4 in	2	2	1	1	6	0	0	0	0	0
Phase II-6 in	4	4	4	4	16	7	4	11	3	3
WT6	5	5	5	5	20	11	4	15	2	2
Phase I-4 in	2	1	1	1	5	8	2	10	0	0
Phase II-6 in	3	4	4	4	15	3	2	5	2	2
WT7	6	6	5	5	22	12	6	18	3	3
Phase I-4 in	2	2	1	1	6	5	2	7	0	0
Phase II-4 in	2	2	2	2	8	3	2	5	2	2
Phase II-6 in	2	2	2	2	8	4	2	6	1	1
YT1	5	6	5	5	21	3	2	5	2	2
Phase I-4 in	2	2	1	1	6	0	0	0	0	0
Phase II-6 in	3	4	4	4	15	3	2	5	2	2
YT2	6	6	5	5	22	10	6	16	3	3
Phase I-4 in	2	2	1	1	6	4	2	6	0	0
Phase II-4 in	2	2	2	2	8	3	2	5	2	2
Phase II-6 in	2	2	2	2	8	3	2	5	1	1
YT3	6	6	5	5	22	13	6	19	3	3
Phase I-4 in	2	2	1	1	6	6	2	8	0	0
Phase II-4 in	2	2	2	2	8	3	2	5	2	2
Phase II-6 in	2	2	2	2	8	4	2	6	1	1
YT4	6	6	5	5	22	11	6	17	3	3
Phase I-4 in	2	2	1	1	6	4	2	6	0	0
Phase II-4 in	2	2	2	2	8	3	2	5	2	2
Phase II-6 in	2	2	2	2	8	4	2	6	1	1
Total	**46**	**47**	**40**	**40**	**173**	**77**	**40**	**117**	**22**	**22**

Table 6 presents the daytime, dry (DD) and nighttime, dry (ND) observations made using the F-150.

Table 6. Disaggregate Count of F-150 Observations

	DD											ND				
Cloud Cover	**No Clouds**				**Some clouds**				**Clouds**			**No Clouds**				
Speed	**50**		**65**		**50**		**65**		**50**			**50**		**65**		
Travel Direction	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**Total**	**NB**	**SB**	**NB**	**SB**	**Total**
WT1	3	2	3	2	0	1	1	2	1	1	16	4	4	4	4	16
4 in	2	1	2	1	0	1	0	1	0	0	8	2	2	2	2	8
6 in	1	1	1	1	0	0	1	1	1	1	8	2	2	2	2	8
WT3	4	4	3	3	0	0	1	1	0	0	16	4	4	4	4	16
6 in	4	4	3	3	0	0	1	1	0	0	16	4	4	4	4	16
WT6	3	3	2	3	1	0	2	1	0	1	16	4	4	4	4	16
6 in	3	3	2	3	1	0	2	1	0	1	16	4	4	4	4	16
WT7	4	4	3	3	0	0	1	1	0	0	16	4	4	4	4	16
4 in	2	2	2	2	0	0	0	0	0	0	8	2	2	2	2	8
6 in	2	2	1	1	0	0	1	1	0	0	8	2	2	2	2	8
YT1	3	3	2	3	1	0	2	1	0	1	16	4	4	4	4	16
6 in	3	3	2	3	1	0	2	1	0	1	16	4	4	4	4	16
YT2	3	2	3	2	0	1	1	2	1	1	16	4	4	4	4	16
4 in	2	1	2	1	0	1	0	1	0	0	8	2	2	2	2	8
6 in	1	1	1	1	0	0	1	1	1	1	8	2	2	2	2	8
YT3	4	4	3	3	0	0	1	1	0	0	16	4	4	4	4	16
4 in	2	2	2	2	0	0	0	0	0	0	8	2	2	2	2	8
6 in	2	2	1	1	0	0	1	1	0	0	8	2	2	2	2	8
YT4	4	4	3	3	0	0	1	1	0	0	16	4	4	4	4	16
4 in	2	2	2	2	0	0	0	0	0	0	8	2	2	2	2	8
6 in	2	2	1	1	0	0	1	1	0	0	8	2	2	2	2	8
Total	**28**	**26**	**22**	**22**	**2**	**2**	**10**	**10**	**2**	**4**	**128**	**32**	**32**	**32**	**32**	**128**

ANALYSIS

Consideration of Non-width Factors Affecting MV Detection Confidence Ratings

Prior to conducting the investigation, researchers anticipated that factors unrelated to the properties of the pavement marking samples themselves could influence the detection confidence rating of the markings by the MV system. These factors included the speed at which the observation was collected, ambient lighting conditions, and direction of travel. Data were collected during the daytime and nighttime, but daytime data collection had varying lighting conditions. These varying conditions were due to the presence of or lack of clouds. The cloud conditions were subjectively documented during the different days of data collection.

Nearly all of the figures included in this section are divided into two directional sections to account for direction-specific sample and lighting characteristics, with the top half of the figure documenting northbound observations and the bottom half reserved for southbound observations (with the exceptions being scenarios where only northbound observations were considered). The northbound and southbound sections have each been divided into two smaller subsections, for a total of four vertically stacked subsections. The top half of each section illustrates the spread of the individual observations for each of the samples via box-and-whisker plots, while the lower half illustrates the average value of the observations for each of the scenarios.

To identify scenarios in which pavement marking width may have a substantial effect, the MV detection confidence ratings for the 4-inch and 6-inch markings were plotted against several performance contrast ratios (marking performance characteristic directly compared to adjacent pavement performance characteristic) that are generally considered to be good indicators of visibility. For daytime markings, the contrast ratios were the luminance (CIE Y), luminance coefficient under diffuse illumination (Qd), and MV geometry daytime luminance (L_v). For nighttime observations, the contrast ratios were coefficient of retroreflected luminance (R_L, retroreflectivity) and MV geometry nighttime luminance (L_v). In the figures, the samples are ordered from left to right in order of ascending value of the contrast ratio. The calculated contrast ratios and the pavement marking performance characteristic are provided for each marking. The samples are ordered from left to right of ascending value of the contrast ratio calculated for the 4-inch wide Phase I markings. The calculated contrast ratios are provided under the phase number for each marking.

The figures contained in the following section are based on the luminance (CIE Y) contrast ratio for daytime observations and retroreflectivity contrast ratio for nighttime observations. These performance metrics were used for several reasons. First, these material properties are among the most readily available options for road agencies to quantify the performance of their road markings. Second, Y and R_L remain consistent within a sample from observation to observation because they are a standard measurement, whereas the luminance measurements using the CCD camera were taken under viewing conditions at the time of the observation. The CCD luminance will vary as the ambient lighting varies because it is not a standard measurement since it relies on an uncontrolled light source. Qd is only observable using a specific retroreflectometer that is yet to be widely adopted in the United States. Plots using Qd and MV geometry daytime or nighttime luminance are provided in Appendix C.

Generally speaking, the ratios were relatively consistent for a given sample (i.e., if a marking had a high CIE Y ratio, it also had a high luminance (L_v) or R_L ratios). Figure 22 presents the dry, daytime contrast ratios by sample. The figure illustrates how the relationship between the various longitudinal pavement markings is relatively consistent regardless of which contrast ratio is considered (e.g., sample WT1 always has larger contrast ratios than sample YT2). This indicates that the findings of this research would be similar regardless of which available performance characteristic contrast ratio is used. The similarities between performance metrics may also suggest that an ideal metric to quantify performance (i.e., one that is more clearly indicative of performance compared to the others) has not been identified. Appendix I provides additional figures representing the contrast ratios for other combinations of lighting and pavement condition. The contrast ratios used in this report are a straight ratio of marking property to pavement property.

Figure 22. Dry, Daytime Contrast Ratio Comparison

Influence of Speed

The speed at which the observations were recorded could potentially affect the detection confidence rating assigned to a sample. During data collection, two speeds (50 and 65 mph) were used to collect data. The Explorer data were examined by the observation speed for each of the six combinations of moisture and lighting in this study. Figure 23 illustrates the performance of the MV relative to vehicle speed for the markings that were both 4- and 6-inches wide during Phase II of the data collection under dry, daytime conditions with respect to speed. The Phase I 4-inch comparison markings are also included, however; it is not reasonable to evaluate the performance of Phase II 6-inch markings directly with Phase I 4-inch markings due to the effect of sun position during the daytime evaluations.

Figure 23 does not indicate a clear trend in the effect of speed on the MV's ability to detect these markings, as some markings had higher detection confidence ratings at high speeds, some lower, and some experienced no change.

Figure 24 illustrates the effect of speed on the Phase II 6-inch-only markings and their Phase I 4-inch comparison markings, for dry daytime conditions. Figure 24 suggests that speed again has no discernible effect on the detection confidence rating, as most markings received approximately the same rating as when observed at 50 and 65 mph. Sample YT1, which had the lowest contrast ratio, had low detection confidence ratings during both phases of the data collection, particularly during the northbound observations.

Figure 25 presents the Phase II 4- and 6-inch markings during dry, nighttime conditions. The Phase I 4-inch comparison markings are also included. With few exceptions, the detection confidence ratings of individual marking samples does not appear to be impacted by speed, nor does speed appear to affect MV performance for a subset of samples with similar properties.

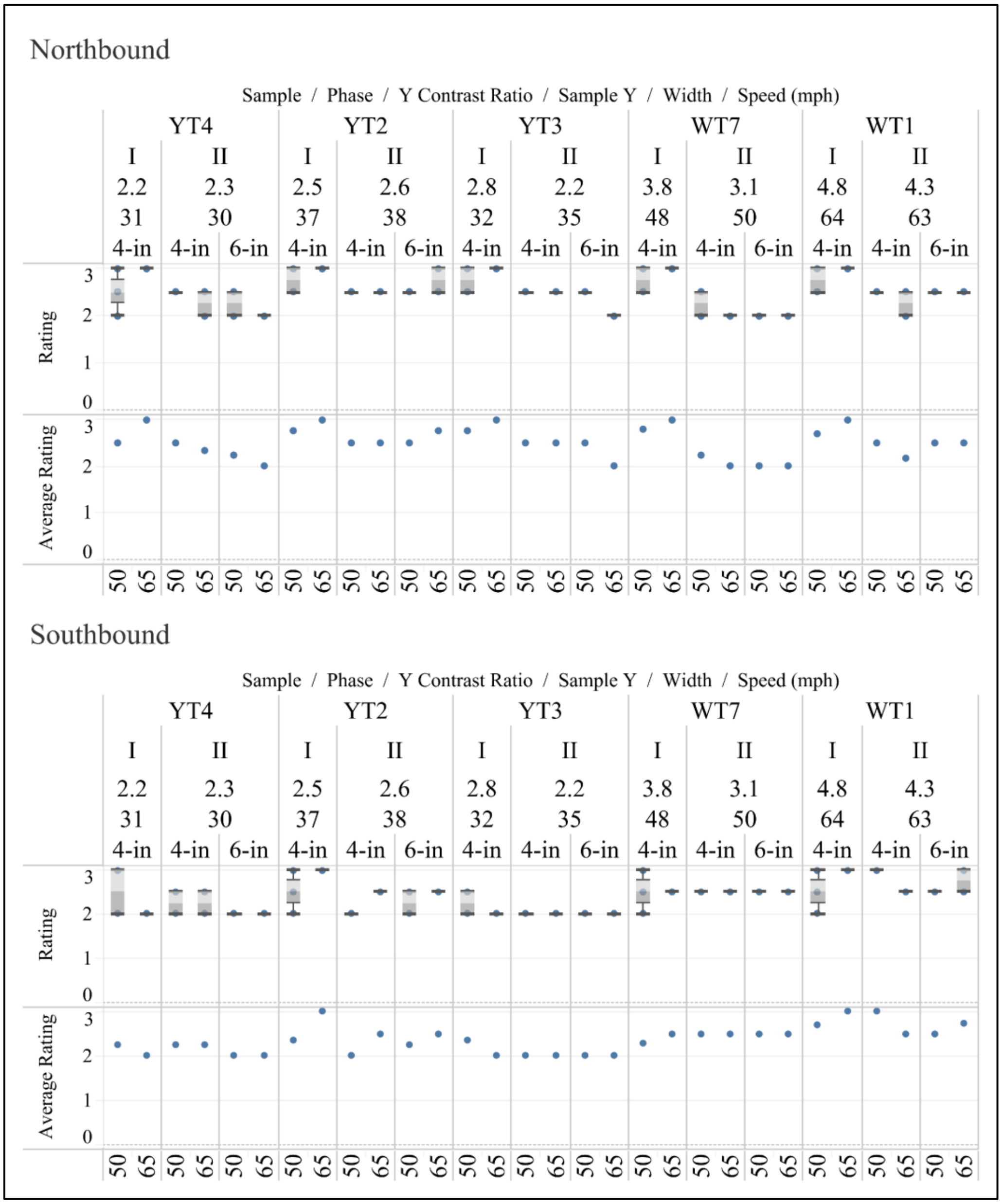


Figure 23. Phase II 4- and 6-inch Markings by Observation Speed, Dry, Daytime Conditions

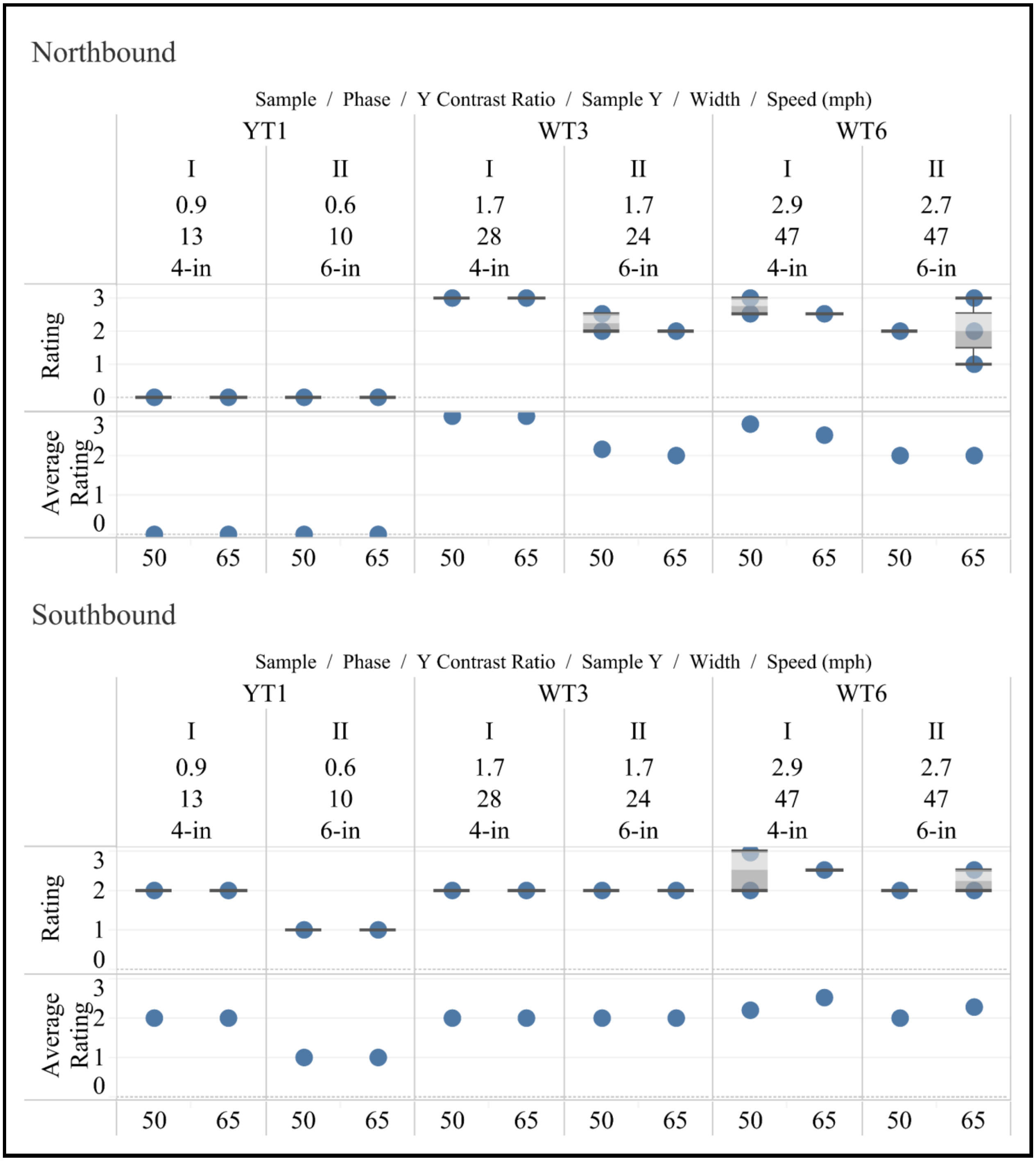


Figure 24. Phase II 6-inch only Markings by Observation Speed, Dry, Daytime Conditions

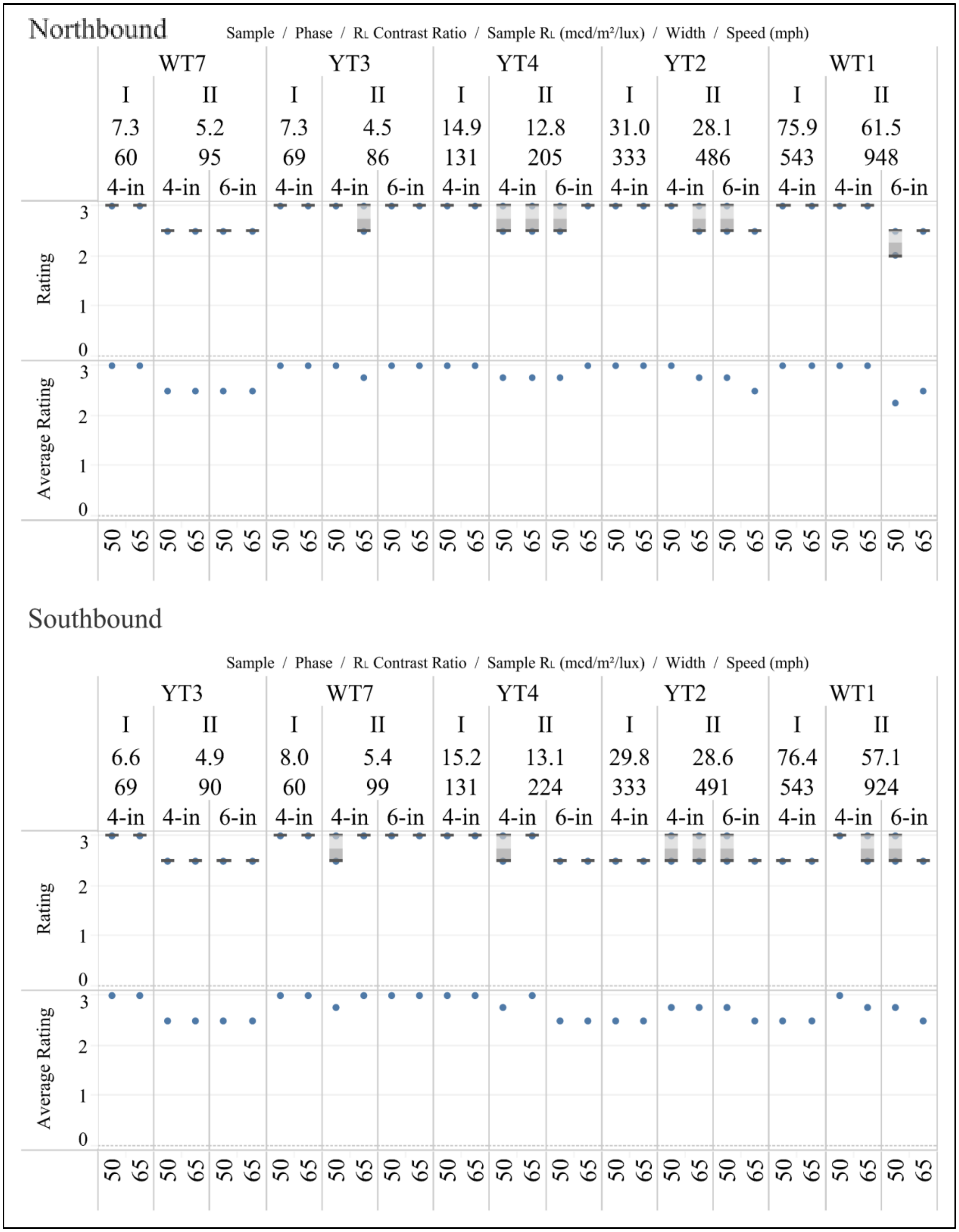


Figure 25. Phase II 4- and 6-inch Markings by Observation Speed, Dry, Nighttime Conditions

Figure 26 presents the observations of the Phase II 6-inch-only samples and their Phase I 4-inch comparison markings, during dry, nighttime conditions. Once again, no discernible effect of speed can be identified. Only two speeds were used in the data collection (50 and 65 mph).

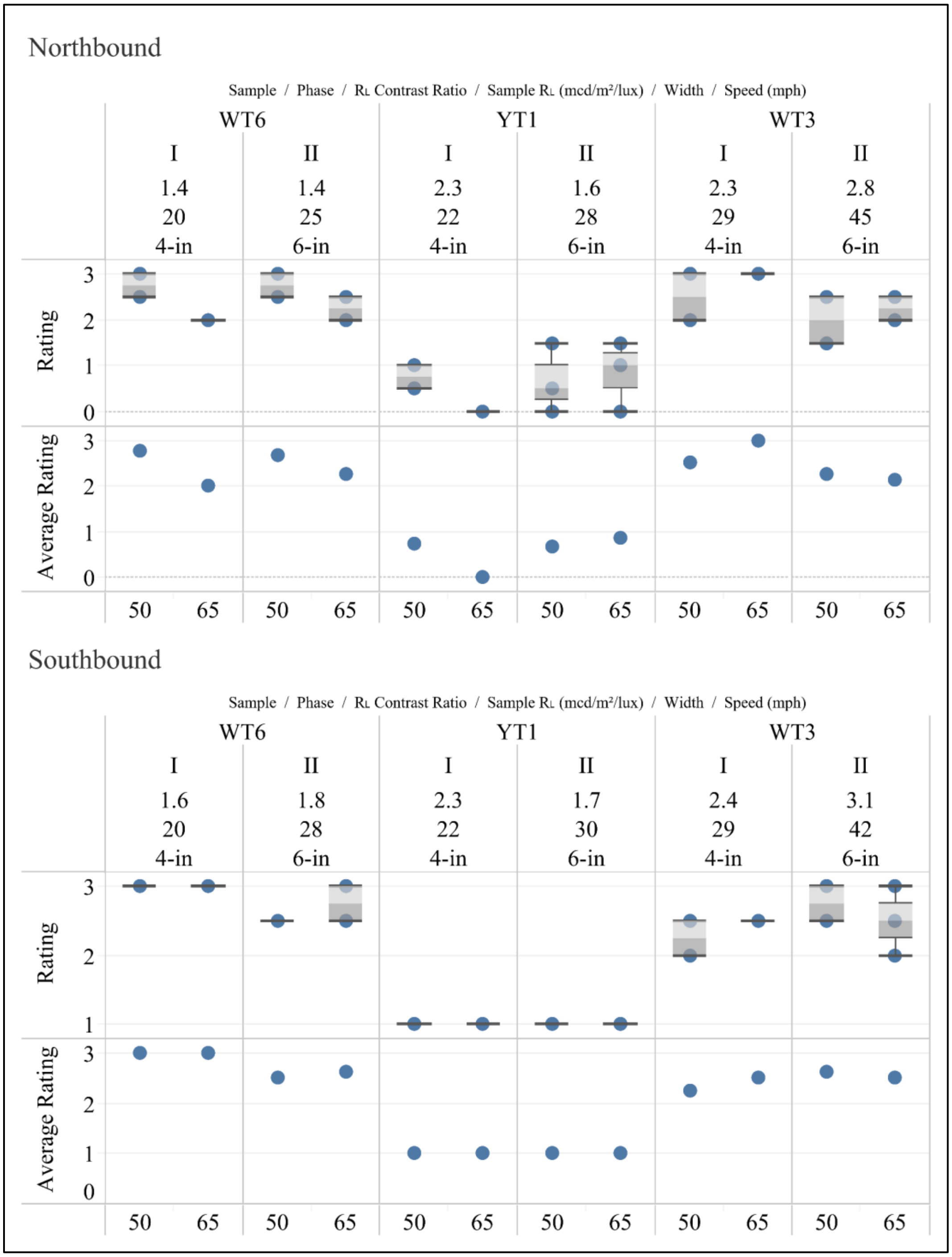


Figure 26. Phase II 6-inch only Markings by Observation Speed, Dry, Nighttime Conditions

Table 7 and Table 8 present tabular summaries of the percent change of the average detection confidence rating of each of the samples attributable to driving at 65 mph as opposed to 50 mph. A negative value indicates a reduction in detection confidence rating. These results are similar to the observations from the figures. The effect of speed is not consistent and mostly minor for the testing conditions evaluated.

Table 7. Percent Change, 50 to 65 mph, Phase II 4- and 6-inch Markings

Dry, daytime						
	Northbound			**Southbound**		
Sample	Phase I 4-in	Phase II 4-in	6-in	Phase I 4-in	Phase II 4-in	6-in
WT1	9.1%	-13.3%	0.0%	9.1%	-16.7%	10.0%
WT7	7.1%	-11.1%	0.0%	8.7%	0.0%	0.0%
YT2	9.1%	0.0%	-20.0%	-15.8%	0.0%	0.0%
YT3	9.1%	0.0%	10.0%	26.3%	25.0%	11.1%
YT4	20.0%	-6.7%	-11.1%	-11.1%	0.0%	0.0%
Dry, nighttime						
	Northbound					
Sample	Phase I 4-in	Phase II 4-in	6-in	Phase I 4-in	Phase II 4-in	6-in
WT1	0.0%	0.0%	11.1%	0.0%	-8.3%	-9.1%
WT7	0.0%	0.0%	0.0%	0.0%	9.1%	0.0%
YT2	0.0%	-8.3%	-9.1%	0.0%	0.0%	-9.1%
YT3	0.0%	25.0%	0.0%	0.0%	0.0%	0.0%
YT4	0.0%	0.0%	9.1%	0.0%	9.1%	0.0%

Table 8. Percent Change, 50 to 65 mph, Phase II 6-inch Markings

Dry, daytime				
	Northbound		**Southbound**	
	Phase I 4-in	6-in	Phase I 4-in	6-in
WT3	0.0%	-5.9%	0.0%	0.0%
WT6	-10.7%	0.0%	13.6%	12.5%
YT1	0.0%	0.0%	0.0%	0.0%
Dry, nighttime				
	Northbound			
	Phase I 4-in	6-in	Phase I 4-in	6-in
WT3	20.0%	-5.6%	11.1%	-4.8%
WT6	-27.3%	-15.6%	0.0%	5.0%
YT1	-100.0%	31.2%	0.0%	0.0%

Influence of Daytime Clouds

The effect of cloud cover was examined on data collected using the Explorer during dry and wet daytime conditions. Cloud cover affects the amount of light that falls on the markings, subsequently affecting glare and possibly producing undesirable conditions. The impact of glare due to the sun was not part of the original data collection plan, but environmental conditions during the data collection efforts were noted. Data collection during both Phase I and Phase II took place during midday with the sun at its maximum overhead position. The Phase II data collection occurred during the summer with the sun in a high position overhead, whereas Phase I data collection occurred during the winter with the sun not as high overhead, but at a position slightly lower in the sky toward the south of the test area.

Figure 27 examined the average detection confidence rating for each sample that was examined as a 4- and 6-inch marking during Phase II data collection for three cloud cover scenarios: no clouds, some clouds (partly cloudy), and clouds (fully cloudy). The samples are ordered in ascending order of Y Contrast Ratio obtained during Phase II of the data collection activities.

The magnitude of the effect of clouds varied from marking to marking. Several markings experienced no effect, while other markings were generally rated higher when clouds were present. This potentially suggests that clouds may reduce the intensity of sunlight on the markings, and potentially reducing glare on the pavement, thus making the markings more detectable by the MV system.

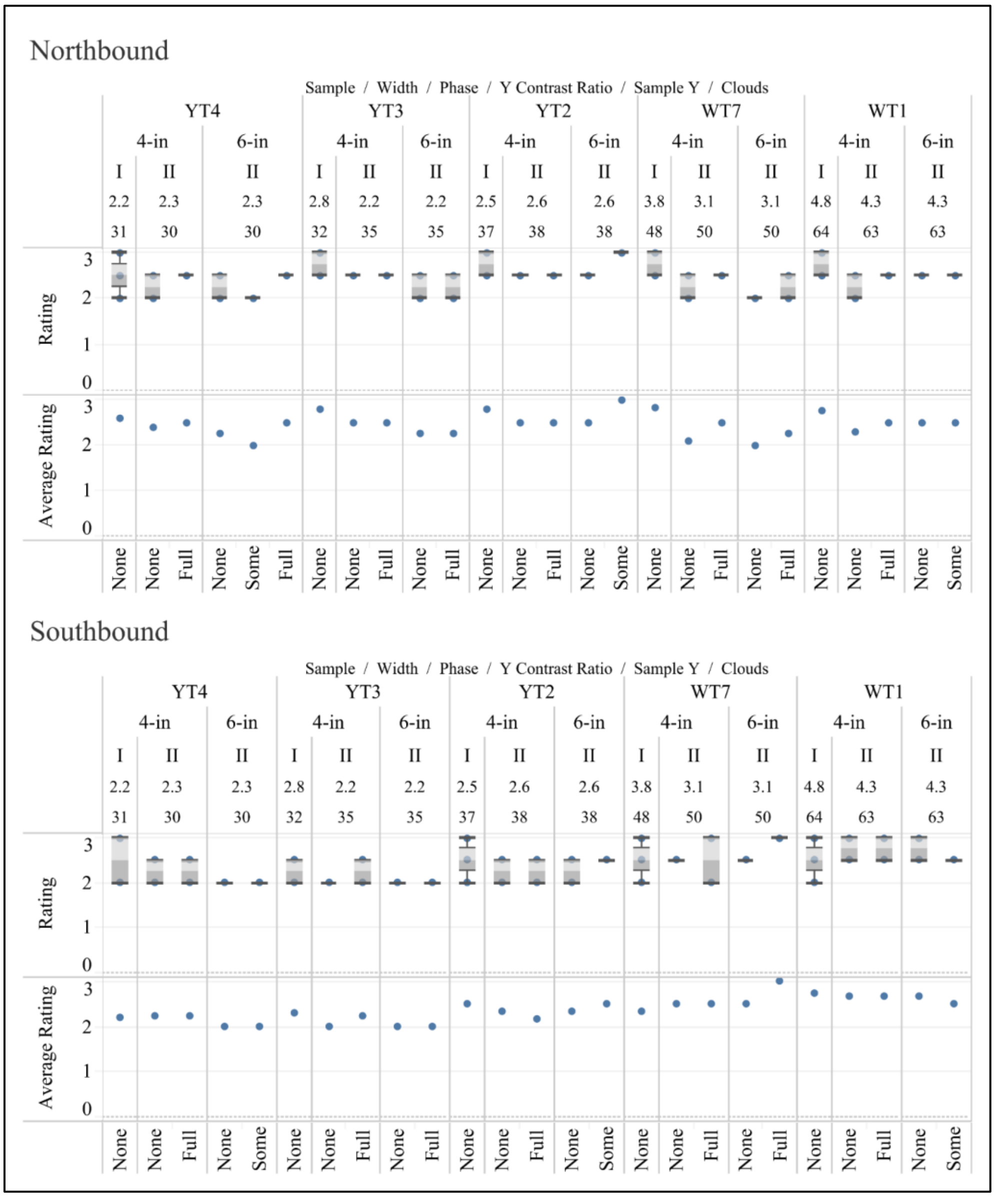


Figure 27. Phase II 4- and 6-inch Markings Dry, Daytime, Cloud Cover Assessment

The samples that were only examined as 6-inch samples during the Phase II data collection period are examined under dry, daytime conditions in Figure 28. A slight increase in detection confidence ratings for cloud presence is shown in some of the samples in Figure 28. For southbound observations of Sample WT3, the presence of some clouds resulted in higher confidence than full cloud conditions.

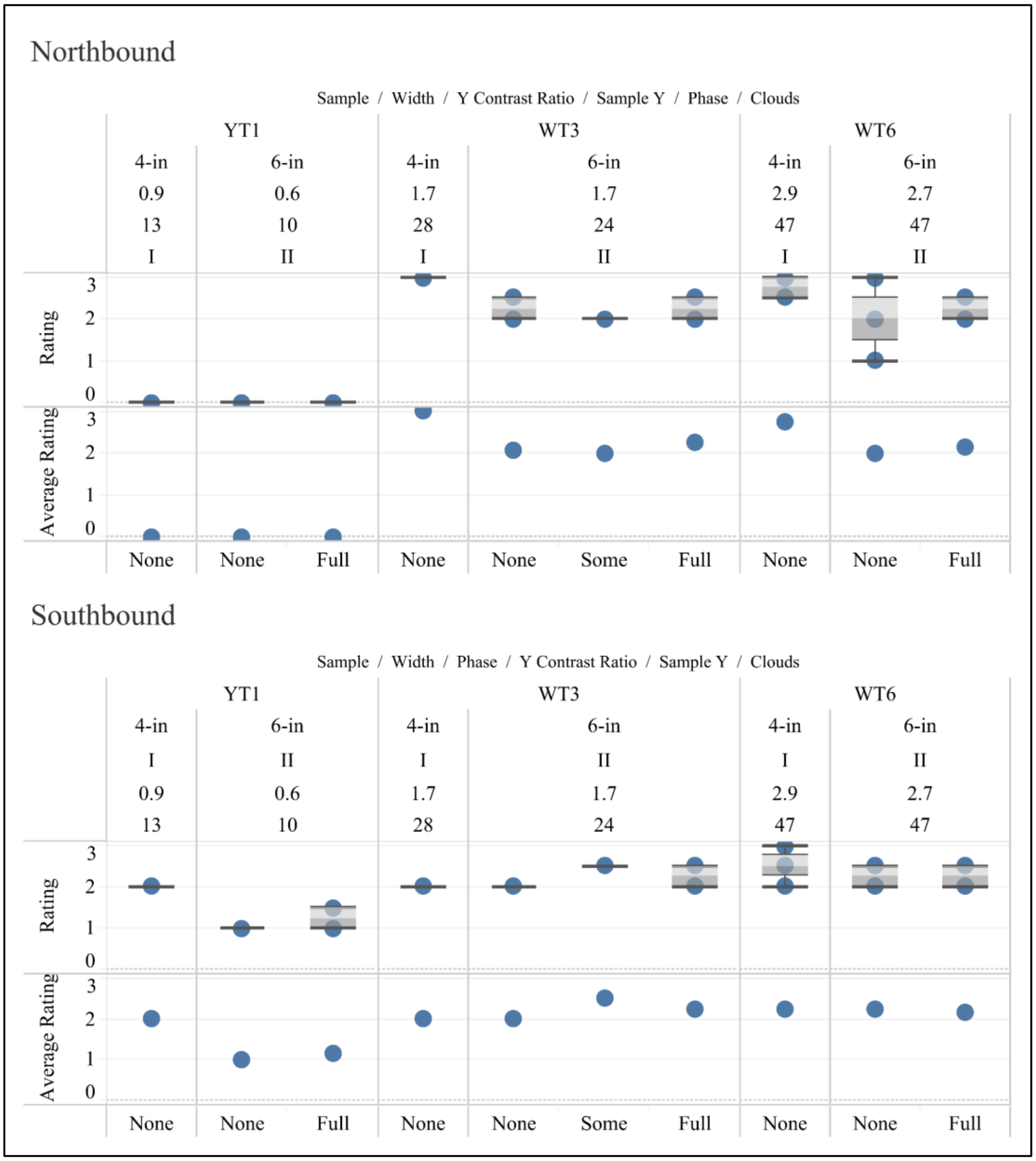


Figure 28. Phase II 6-inch Markings Dry, Daytime, Cloud Cover Assessment

Figure 29 examines the Phase II 4- and 6-inch samples during wet, daytime conditions. The effect of cloud cover under wet, daytime conditions does not indicate a clear relationship between cloud cover and the detection confidence rating assigned to the longitudinal pavement markings by the MV system. While some samples appear to perform better in the presence of clouds, others appear to perform worse. The cloud conditions were somewhat variable and the specific quantity of clouds was not quantified. Additionally, the structure of the marking, which was not quantified in this research, could play a role in performance variation from sample to sample.

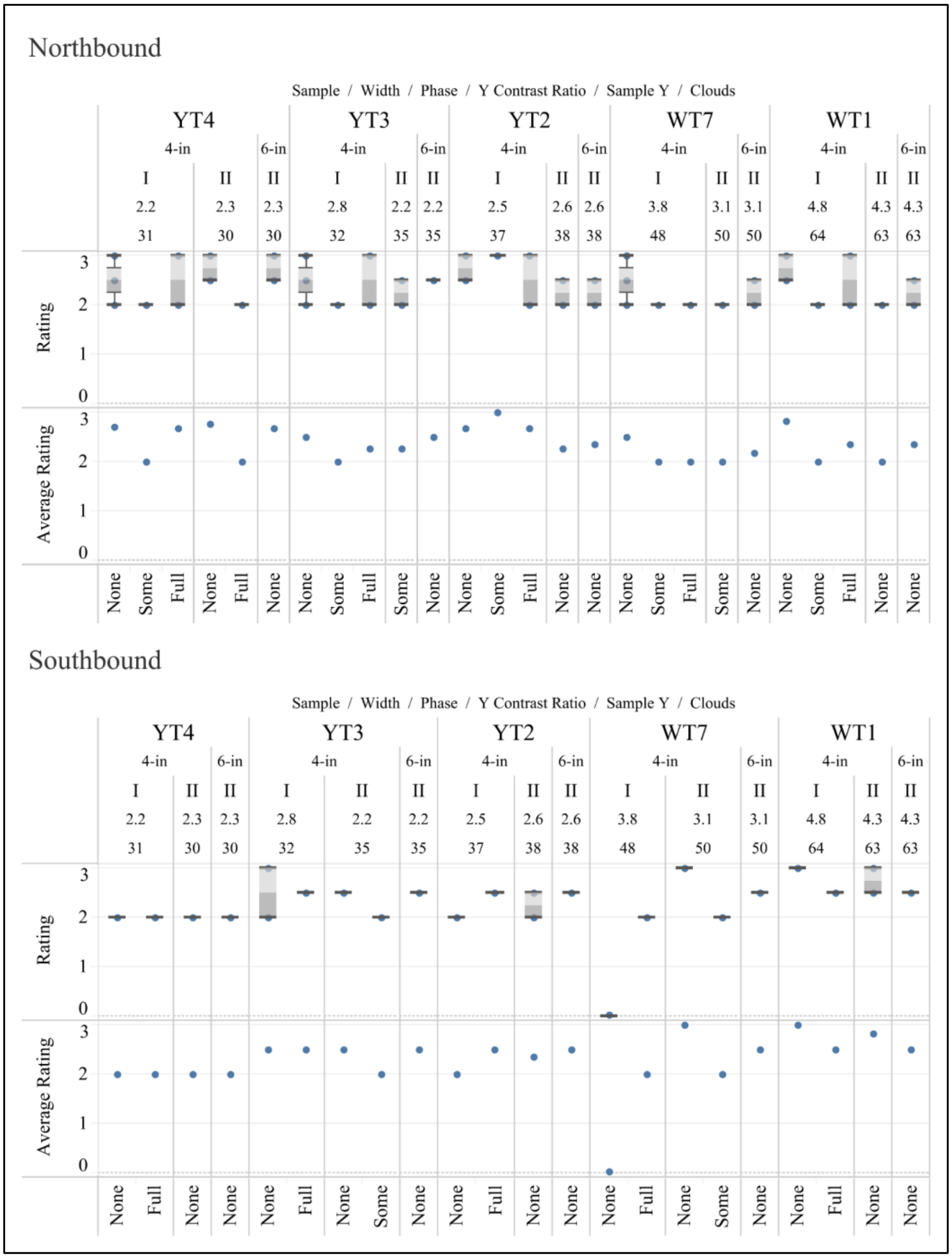


Figure 29. Phase II 4- and 6-inch Markings Wet, Daytime, Cloud Cover Assessment

Figure 30 examines the Phase II 6-inch samples under wet, daytime conditions. Figure 30 supports the information from Figure 29, as the effect of cloud cover varies by sample and direction. Samples YT1 and WT3 were not observed under wet, daytime conditions during Phase I.

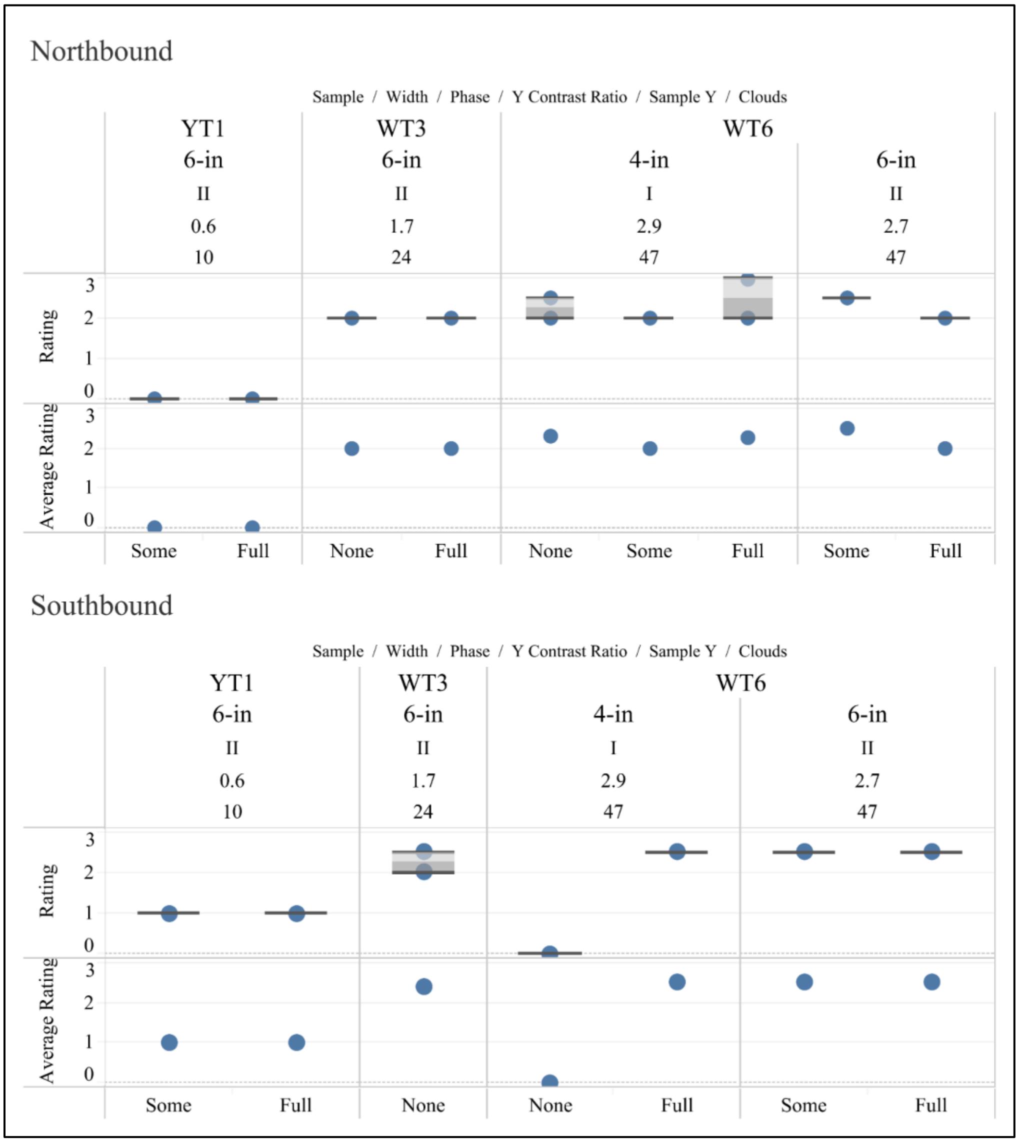


Figure 30. Phase II 6-inch Markings Wet, Daytime, Cloud Cover Assessment

Table 9 through Table 11 are tabular representations of the percent change between the average detection confidence rating of each of the samples based on the cloud cover present. The percent change is compared to the sunny condition. A negative value indicates a reduction in detection confidence rating. In many cases a comparison could not be made due to the limited data available between the different cloud cover conditions. The number of samples with positive, negative, or no effect are similar.

Table 9. Percent Change Based on Cloud Cover, Phase II 4- and 6-inch Markings, Daytime, Dry

	Northbound					
	Phase I 4-in		Phase II 4-in		6-in	
Sample	Some Clouds	Full Clouds	Some Clouds	Full Clouds	Some Clouds	Full Clouds
WT1	-	-	-	8.7%	0.0%	-
WT7	-	-	-	19.0%	-	12.5%
YT2	-	-	-	0.0%	20.0%	-
YT3	-	-	-	0.0%	-	0.0%
YT4	-	-	-	4.2%	-11.1%	11.1%
	Southbound					
	Phase I 4-in		Phase II 4-in		6-in	
Sample	Some Clouds	Full Clouds	Some Clouds	Full Clouds	Some Clouds	Full Clouds
WT1	-	-	-	0.0%	-6.3%	-
WT7	-	-	-	0.0%	-	20.0%
YT2	-	-	-	-7.1%	7.2%	-
YT3	-	-	-	12.5%	-	0.0%
YT4	-	-	-	0.0%	0.0%	-
(-) Indicates insufficient information to compare conditions						

Table 10. Percent Change Based on Cloud Cover, Phase II 4- and 6-inch Markings, Daytime, Wet

	Northbound					
	Phase I 4-in		Phase II 4-in		6-in	
Sample	Some Clouds	Full Clouds	Some Clouds	Full Clouds	Some Clouds	Full Clouds
WT1	-29.4%	-17.6%	-	-	-	-
WT7	-20.0%	-20.0%	-	-	-	-
YT2	12.5%	0.0%	-	-	-	-
YT3	-20.0%	-10.0%	-	-	-	-
YT4	-25.9%	-1.2%	-	-27.3%	-	-
	Southbound					
	Phase I 4-in		Phase II 4-in		6-in	
Sample	Some Clouds	Full Clouds	Some Clouds	Full Clouds	Some Clouds	Full Clouds
WT1	-	-16.7%	-	-16.7%	-	-
WT7	-	Infinite	-33.3%	-	-	-
YT2	-	25.0%	-	-	-	-
YT3	-	0.0%	-20.0%	-	-	-
YT4	-	0.0%	-	-	-	-
(-) Indicates insufficient information to compare conditions						

Table 11. Percent Change Based on Cloud Cover, Phase II 6-inch Markings, Dry and Wet, Daytime

Dry, daytime								
	Northbound				**Southbound**			
	Phase I 4-in		6-in		Phase I 4-in		6-in	
Sample	Some Clouds	Full Clouds	Some Clouds	Full Clouds	Some Clouds	Full Clouds	Some Clouds	Full Clouds
WT3	-	-	-3.4%	8.6%	-	-	25.0%	12.5%
WT6	-	-	-	6.3%	-	-	-	-2.1%
YT1	-	-	-	0.0%	-	-	-	16.7%
Wet, daytime								
	Northbound				**Southbound**			
	Phase I 4-in		6-in		Phase I 4-in		6-in	
Sample	Some Clouds	Full Clouds	Some Clouds	Full Clouds	Some Clouds	Full Clouds	Some Clouds	Full Clouds
WT3	-	-	-	0.0%	-	-	-	-
WT6	-12.2%	-1.2%	-	-	-	Infinite	-	-
YT1	-	-	-	-	-	-	-	-
(-) Indicates insufficient information to compare conditions								

Evaluation of Detection Confidence Rating Relative to Pavement Marking Width

Following the review of the potentially confounding factors previously discussed, additional plots were created specifically for speeds of 50 mph and no clouds (although partial clouds have been included in a few instances to allow for a complete a representation of widths in each data collection period due to limited data on some samples in specific conditions.

Daytime Dry Conditions

Figure 31 presents the pavement marking observations that were recorded during daytime when the pavement was dry, as observed using the Ford Explorer.

Across most of the preformed tape pavement markings, the average detection confidence rating of the 4-inch marking decreased from Phase I to Phase II. This is potentially attributable to differences in sun position. Considering only the Phase II observations, marking samples YT4, WT7, and WT1 were rated approximately the same or less visible as 6-inch pavement markings versus 4-inch pavement markings. Marking sample YT2 was approximately the same or slightly more visible as a 6-inch marking. Marking sample YT3 was approximately the same as both a 4 and 6-inch marking.

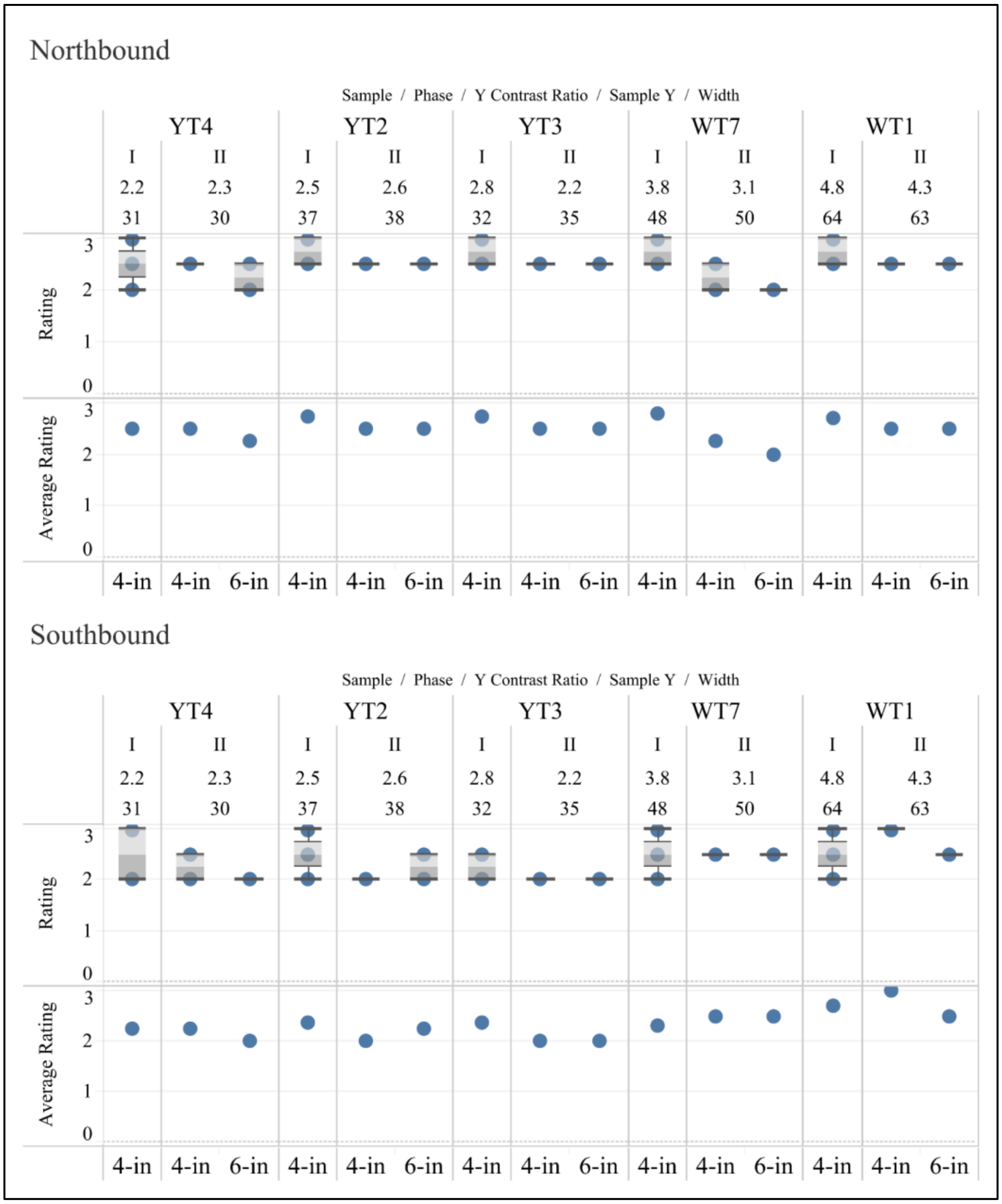


Figure 31. Dry, Daytime Observations, 4-inch Phase I vs. 4-inch and 6-inch Phase II

The pavement markings were also assessed using a Ford F-150 during the Phase II data collection period (the F-150 MV system was not installed during the Phase I data collection). Figure 32 shows the observations made using both vehicles in a side-by-side format.

In comparison to data from the Explorer shown in Figure 31, the detection confidence ratings in Figure 32 obtained from the MV system in the F-150 were typically lower. There is some variation in this pattern among the southbound observations. This finding may suggest that the MV system evaluated is installation sensitive due to the different viewing geometries. One advantage of the F-150 data as opposed to the Explorer data was the format of the data output. The data from the Explorer relied on human interpretation of the confidence ratings displayed on the data acquisition system, while the F-150 output time-stamped observations in a CSV file. Samples evaluated with the explorer showed a similar impact of marking width on detection confidence as the seen with the explorer data.

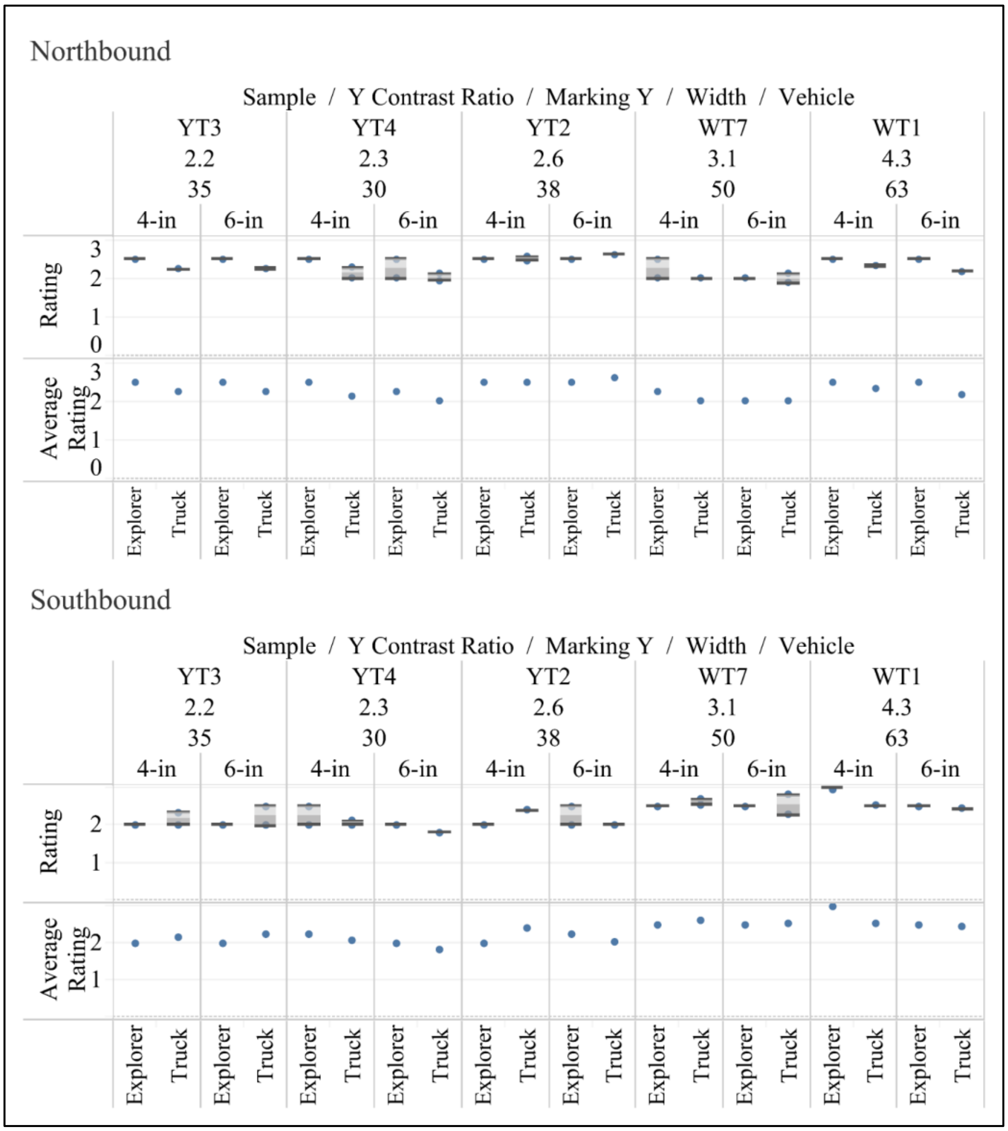


Figure 32. Dry, Daytime Observations of 4- and 6-inch Markings by Explorer and F-150

Figure 33 is a compilation of the observations of samples YT1, WT3, and WT6, which were examined only as 6-inch markings during Phase II.

Sample YT1 received low detection confidence ratings, particularly during northbound observations. Marking samples WT3 and WT6 both had lower detection confident ratings as six inch markings during northbound observations and performed equally well during southbound observations when compared to the 4-inch markings.

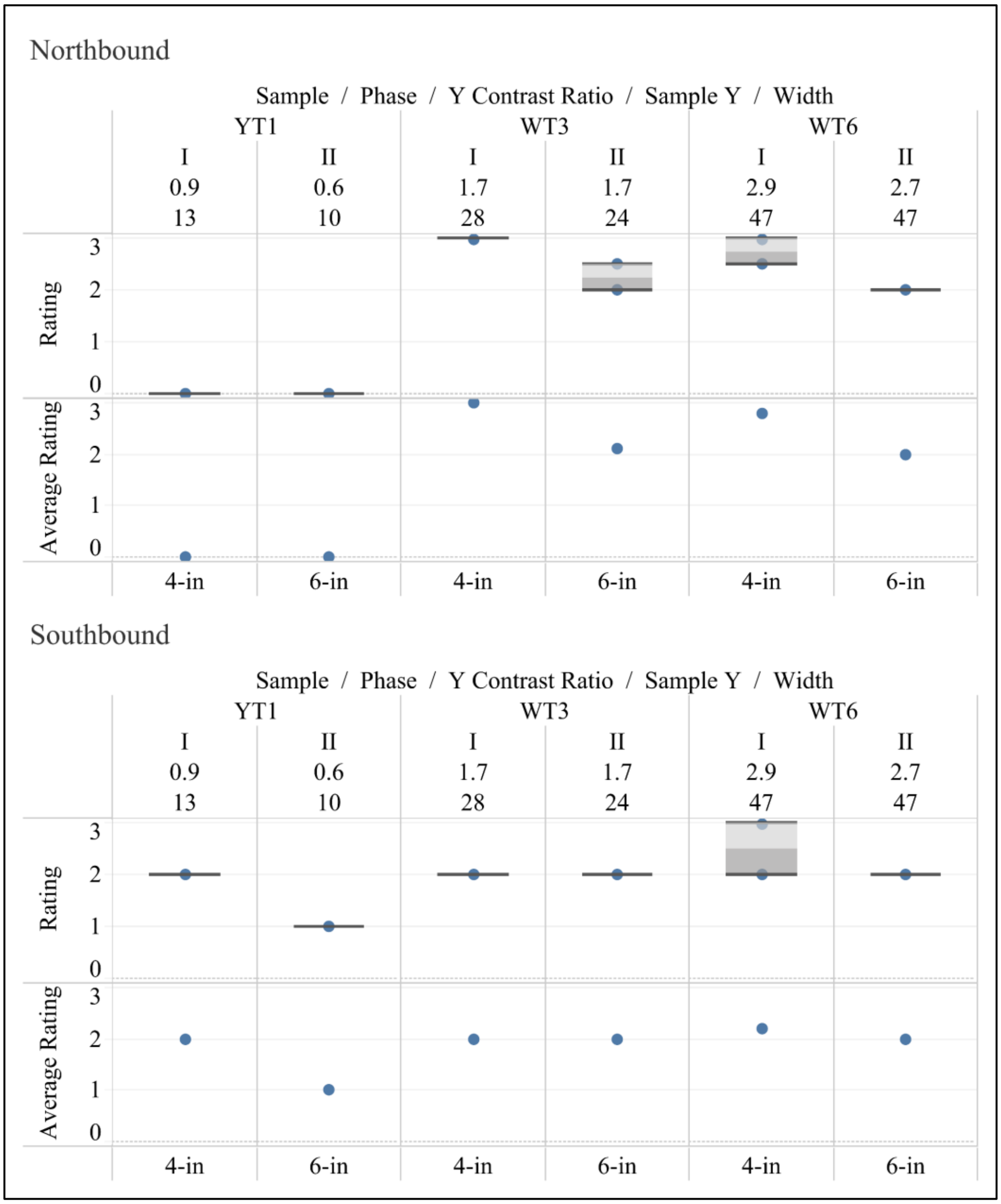


Figure 33. Dry, Daytime Observations, 4-inch Phase I vs 6-inch Phase II, Explorer Only

Daytime Wet Conditions
The pavement markings were tested in wet conditions to determine if the 6-inch wide markings impacted the detection confidence ratings while the markings and road surface were wet. Figure 34 provides the results of the MV systems ability to detect the various marking samples in a daytime wet condition. Wet conditions were only examined using the Explorer. Note that to provide representation across all samples, observations during partially cloudy skies were included in the northbound plot. Subsequently, the results shown for northbound samples YT3 and WT7 as 4-inch markings are based on partially cloudy skies, while the other observations are essentially unaffected.

With the exception of markings YT2 and WT7 (northbound) and WT1 (in both directions), the markings performed better during Phase II data collection versus Phase I. Only marking WT7 had observations rated as 0 during the Phase I data collection. Similar to the observations during daytime dry conditions, this suggests that the position of the sun may have influenced the detectability of the markings by the MV system. The northbound 6-inch markings were detected with similar or higher confidence ratings then the 4-inch markings when just considering Phase II data. The southbound 6-inch markings were detected with similar or higher confidence ratings (sample WT1 is an exception) then the 4-inch markings, when just considering Phase II data.

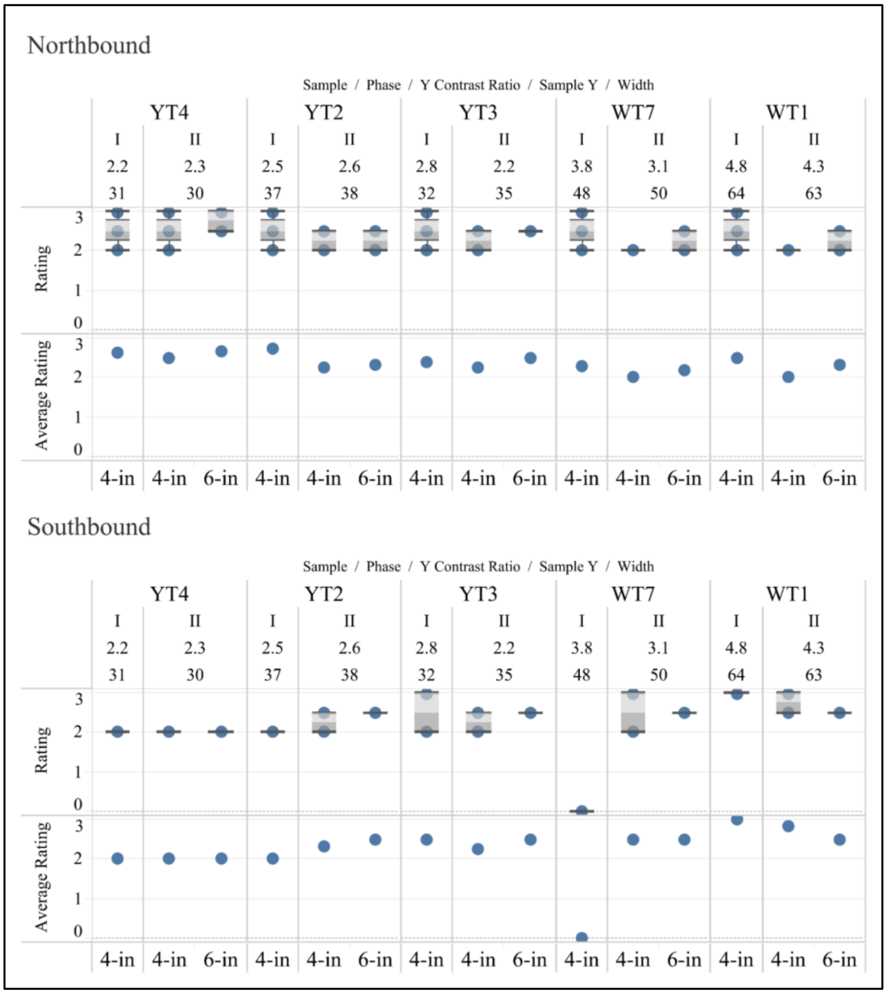


Figure 34. Wet, Daytime Observations, 4-inch Phase I vs. 4- and 6-inch Phase II

Figure 35 provides an example of the glare caused by the sun that affected some of the testing during the Phase I data collection. The left image is facing southbound toward the midday wintertime sun. The right image is the same section, facing northbound. The images were taken at nearly the same time after the conclusion of the wet daytime testing. The water on the road added to the glare caused by the sun and resulted in poor detection of some of the markings. The Phase II data collection occurred during the summer with the sun in a much higher position during the midday data collection. This resulted in differing glare conditions during the two phases.

Figure 35. Daytime Wet Glare Phase I, Facing South (left), North (right).

Figure 36 illustrates the daytime, wet observations of the samples observed only as 6-inch markings during Phase II.

Figure 36 illustrates that sample WT6 performed much better under wet conditions during southbound observations as a 6-inch marking compared to the 4-inch marking. Samples YT1 and WT3 did not have comparable wet daytime 4-inch wide observation during Phase I. Sample YT1, which had the lowest CIE Y contrast ratio, performed poorly during both north- and southbound observations.

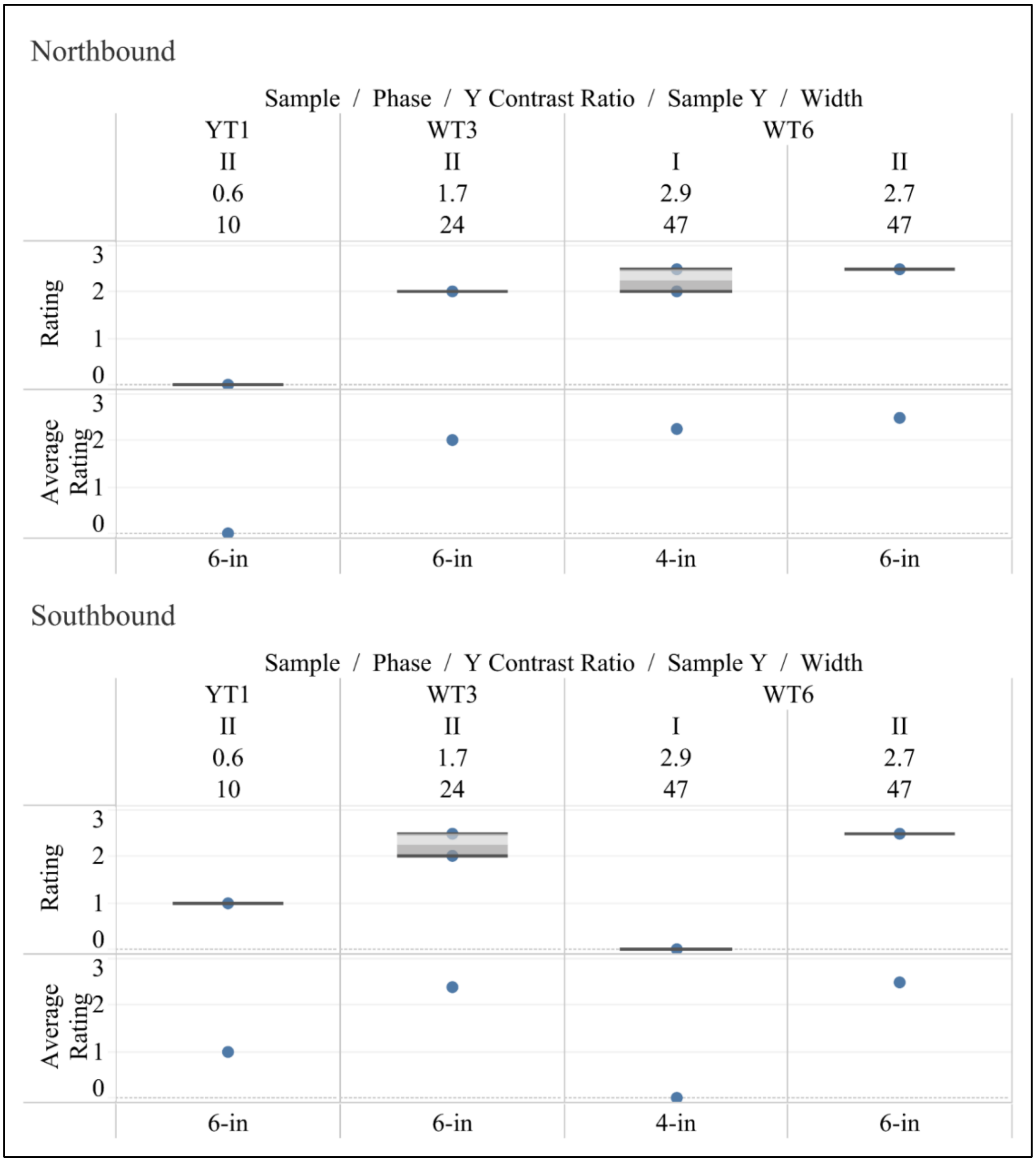


Figure 36. Wet, Daytime Observations, 4-inch Phase I vs. 6-inch Phase II, Explorer Only

Nighttime Dry Conditions

Figure 37 documents the detection confidence ratings for the pavement markings during dry conditions at night.

Pavement marking samples WT7 northbound and YT4 northbound had lower detection confidence ratings in the Phase II 4-inch data collection versus the Phase I data collection, while the same can be said for WT7, YT3, and YT4 southbound. YT2 and WT1 both had higher detection confidence ratings during Phase II as 4-inch markings compared to Phase I. This is somewhat counterintuitive, as the sun does not play a role in visibility at night and thus the expectation is that detection confidence ratings should be the same for the same width and sample of marking. This is potentially attributable to the subjective nature of the data reduction process, variability in the data collected, or slight differences in the markings evaluated or data collection procedure. Samples YT2 northbound, YT4 southbound, and WT1 had lower detection confidence ratings as 6-inch markings compared to the 4-inch markings. Sample WT7 northbound had a higher detection confidence rating as a 6-inch marking compared to the 4-inch marking. The other sample shad similar detection confidence ratings as 4 and 6-inch markings.

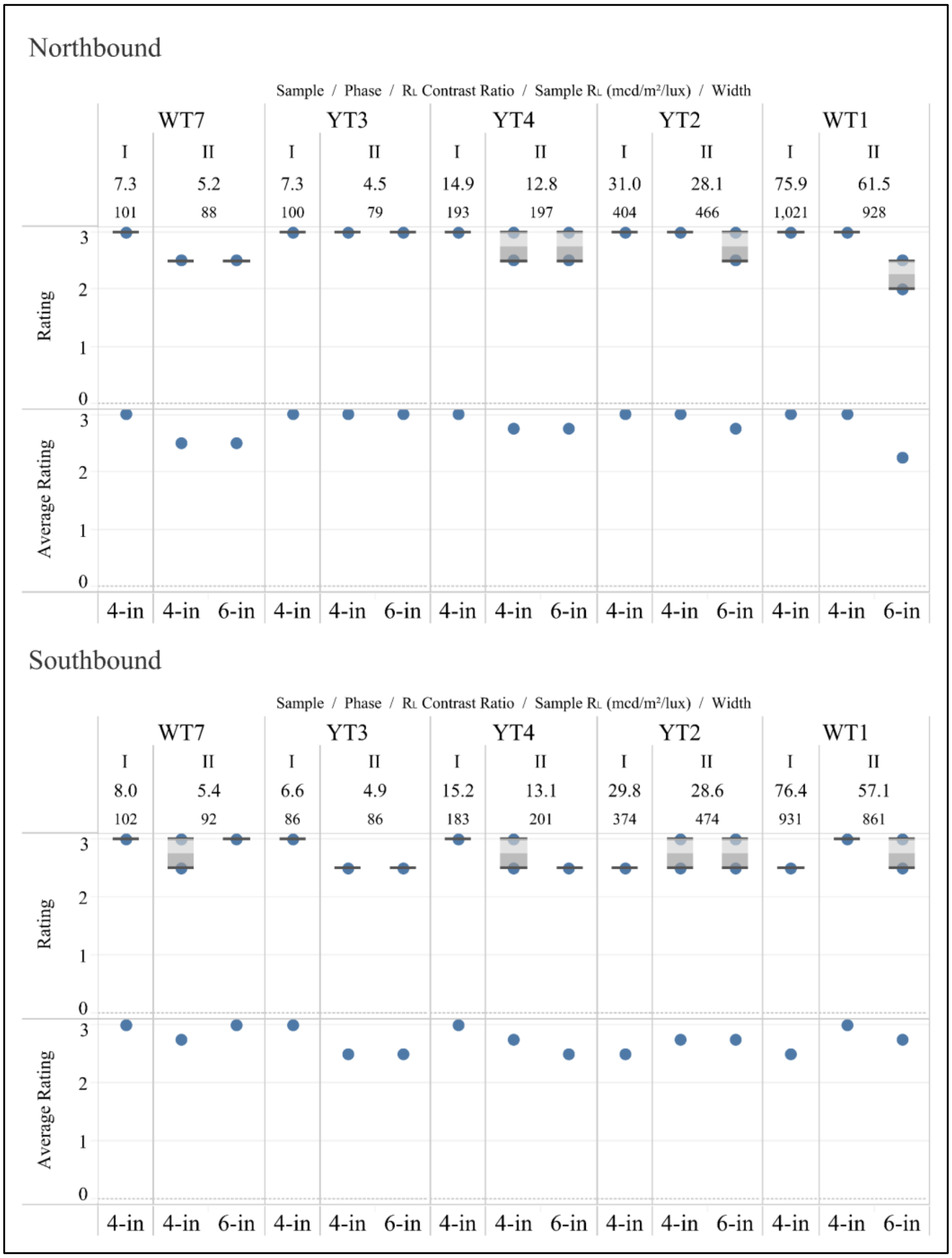


Figure 37. Dry, Nighttime Observations, 4-inch Phase I vs. 4- and 6-inch Phase II

Observations were made using the F-150, and are presented side-by-side with the Explorer observations in Figure 38. The observations from the F-150 are again typically lower than those from the Explorer. MV installation and vehicle differences (e.g., headlight aim, intensity, and observation geometry) likely played a role in these discrepancies. Samples YT3, YT4 southbound, YT2 southbound, and WT7 all had higher detection confidence rating as 6-inch markings compared to the 4-inch markings when evaluated by the F-150. Sample WT1 had lower detection confidence ratings as a 6-inch marking. The other sample shad similar detection confidence ratings for the 4 and 6-inch markings.

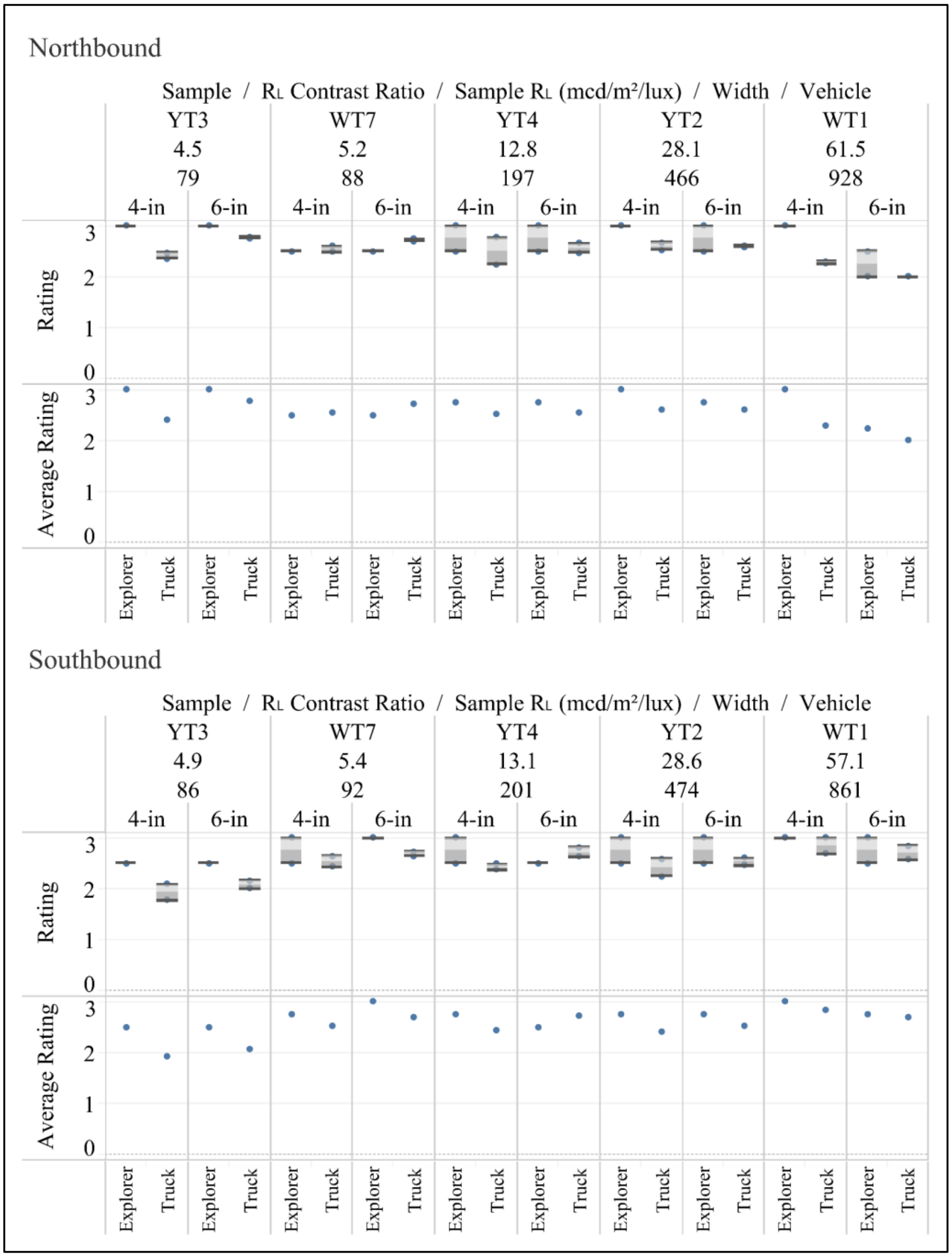


Figure 38. Dry, Nighttime Observations, 4- and 6-inch Markings by Explorer and F-150

Figure 39 illustrates the detection confidence ratings of the Phase II 6-inch only markings at night under dry conditions. Sample YT1 much lower detection confidence ratings than the other samples, despite having a comparable R_L contrast ratio. This suggests that factors other than R_L play a role in MV detection confidence of pavement markings. Sample F performed relatively comparably as a 4- and 6-inch marking. Sample WT3 northbound had higher detection confidence ratings as a 6-inch inch marking. Samples WT6 southbound and WT3 northbound had lower detection confidence ratings as 6-inch markings. The other samples had similar detection confidence ratings as 4 and 6-inch markings.

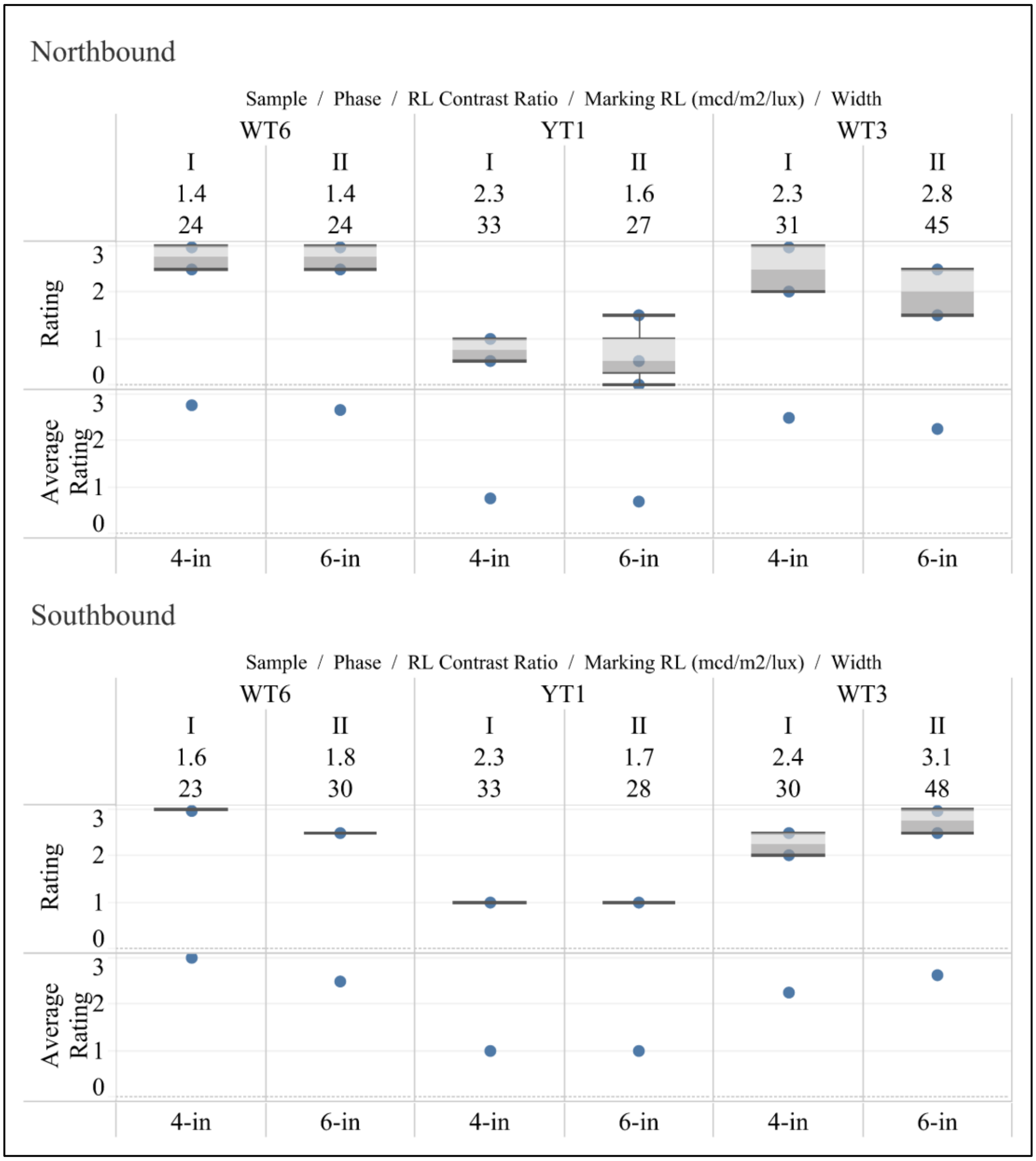


Figure 39. Dry, Nighttime Observations, 4-inch Phase I vs. 6-inch Phase II, Explorer Only

Nighttime Wet Conditions

Figure 40 captures the marking detection confidence ratings at night with wet pavement. Similar to the information presented in Figure 37, Figure 40 demonstrates relatively consistent high detection confidence ratings across the range of pavement markings during the Phase I and Phase II data collection periods. Although marking sample YT2 northbound had a higher detection confidence rating as a 6-inch marking, the other samples had lower or similar detection confidence ratings as 6-inch markings when compared to the 4-inch markings.

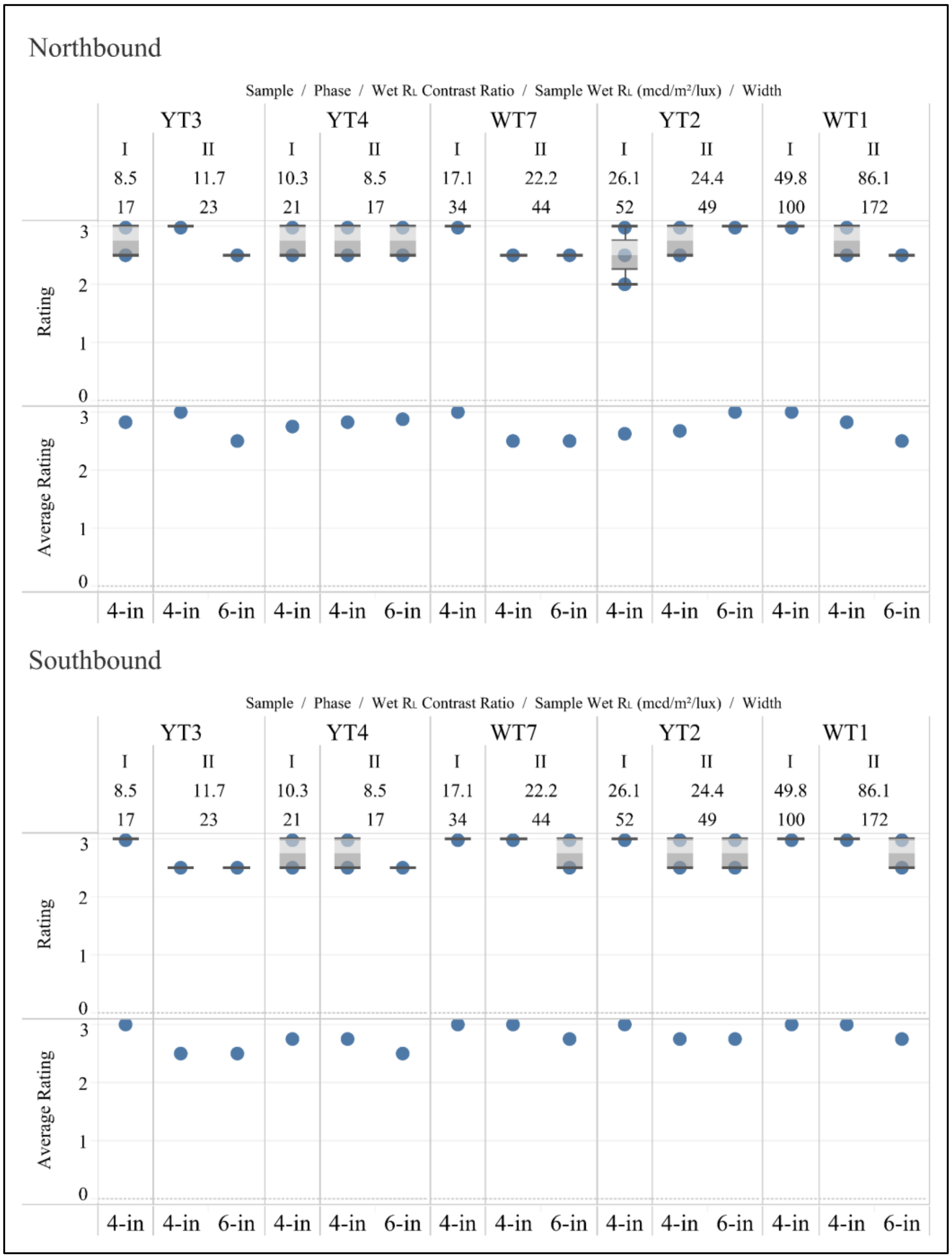


Figure 40. Wet, Nighttime Observations, 4-inch Phase I vs. 4- and 6-inch Phase II

Figure 41 presents the detection confidence ratings of the Phase II 6-inch only markings under nighttime wet conditions. Sample WT6 northbound had an increased detection confidence rating as a 6-inch marking. Sample YT1 performed poorly, similarly to the dry, nighttime conditions.

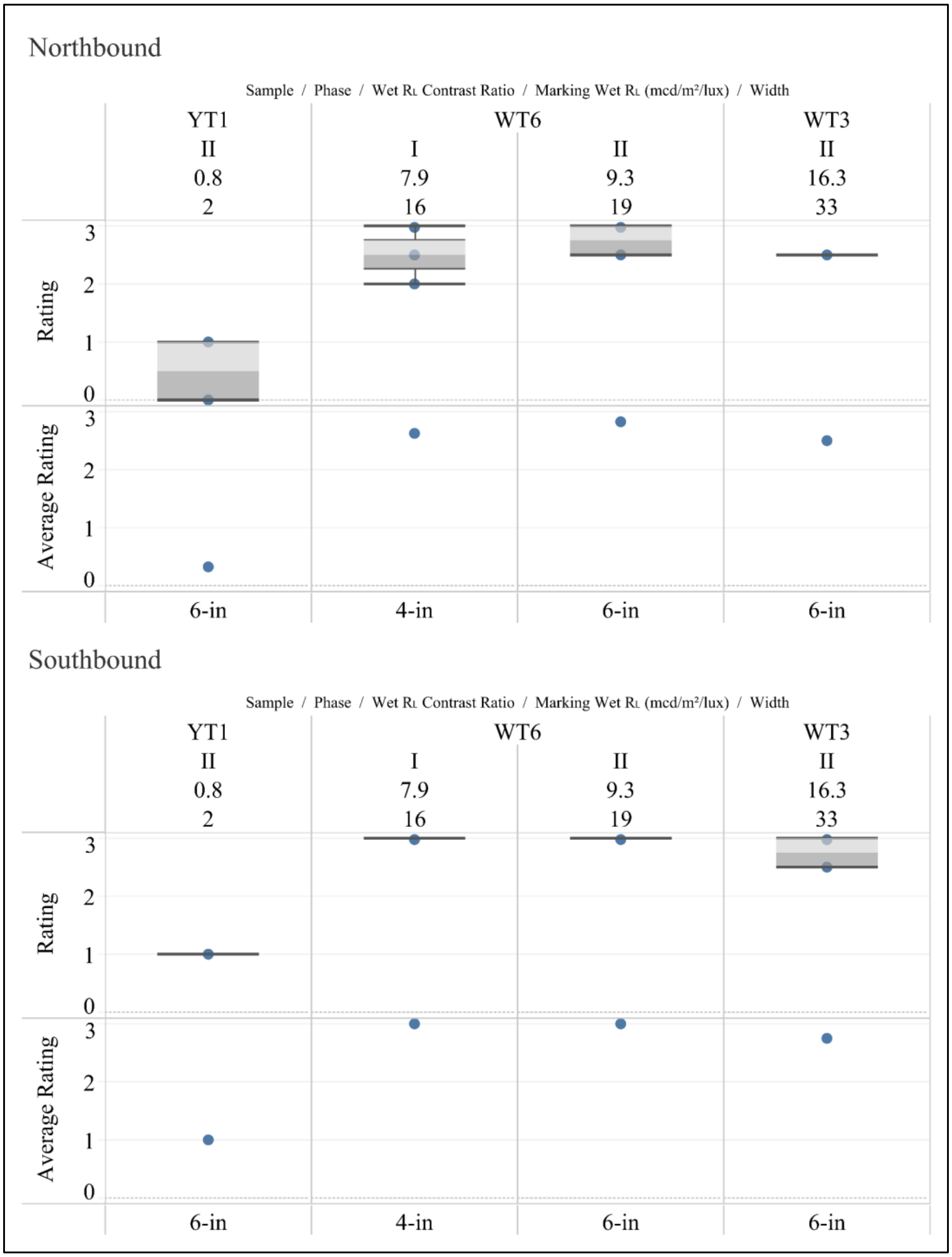


Figure 41. Wet, Nighttime Observations, 4-inch Phase I vs. 6-inch Phase II

Nighttime Dry Glare Conditions

Figure 42 displays the detection confidence ratings of the markings during dry conditions at night, with glare applied to the markings by an opposing vehicle. The Phase II evaluation had a glare source applied for select tests when the markings were both 4 and 6-inches wide. The lack of spread in the data is indicative of the relatively low number of observations taken under this scenario.

Generally speaking, all five of the markings had high detection confidence ratings as 4-inch markings. Marking samples WT7, WT1 an YT2 had lower detection confidence ratings as 6-inch markings. The average detection confidence ratings of 2.5 are indicative of the fact that the lane model developed by the MV system became more reliable as the exposure to the pavement markings increased. The MV system would typically assign a detection confidence rating of 2 over the first half of the marking section, while assigning a 3 beyond the halfway point, resulting in the overall 2.5 average. Slight differences in the location and angle of the glare source vehicle could be contributing factors for these differences.

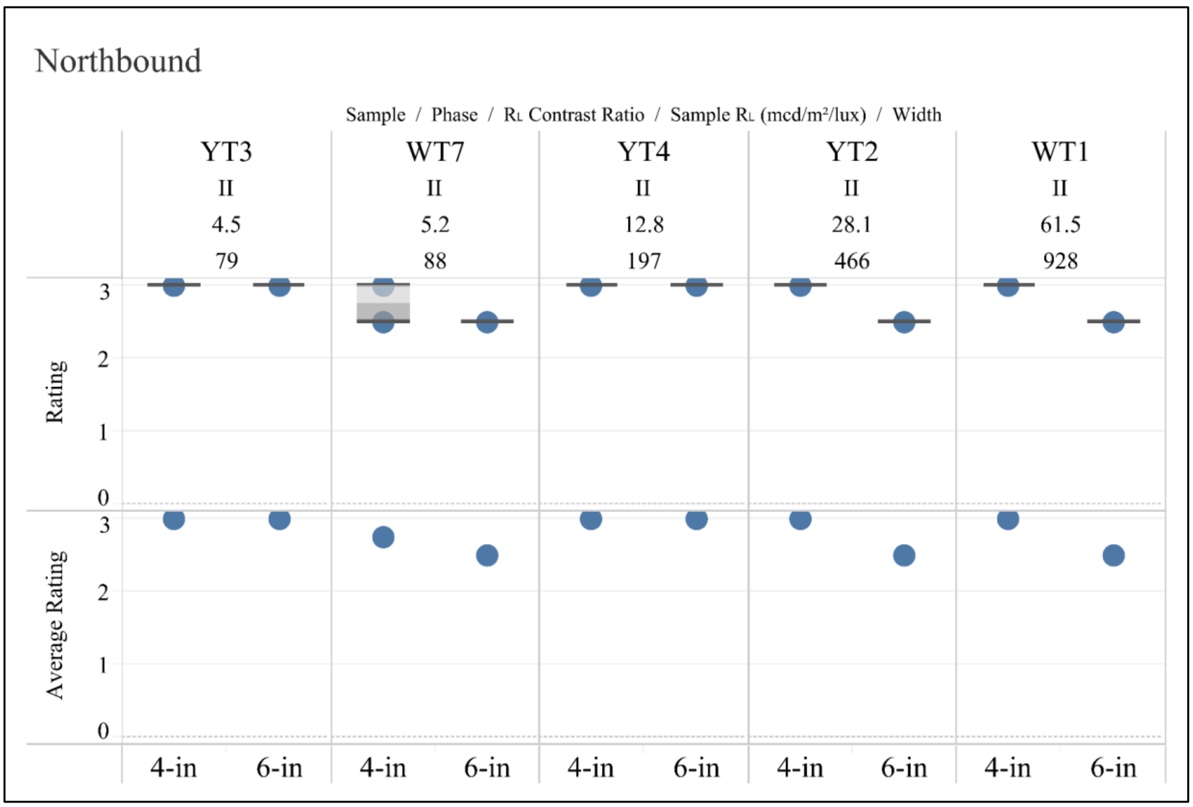


Figure 42. Dry, Nighttime, Glare Observations, 4- and 6-inch Phase II

Nighttime Wet Glare Conditions

Figure 43 presents the detection confidence ratings observed during wet conditions at night with glare applied. Figure 43 illustrates that all marking samples had similar or lower detection confidence ratings as 6-inch markings compared to 4-inch markings during the data collection. Marking sample YT3 performed the worst as a 6-inch marking, which is surprising given that it performed as one of the best as a 4-inch marking. Differences in the condition of wetness of the markings or differences in pooled areas of water, and associated glare off the water, could be contributing factors to differences in observation during the wet conditions.

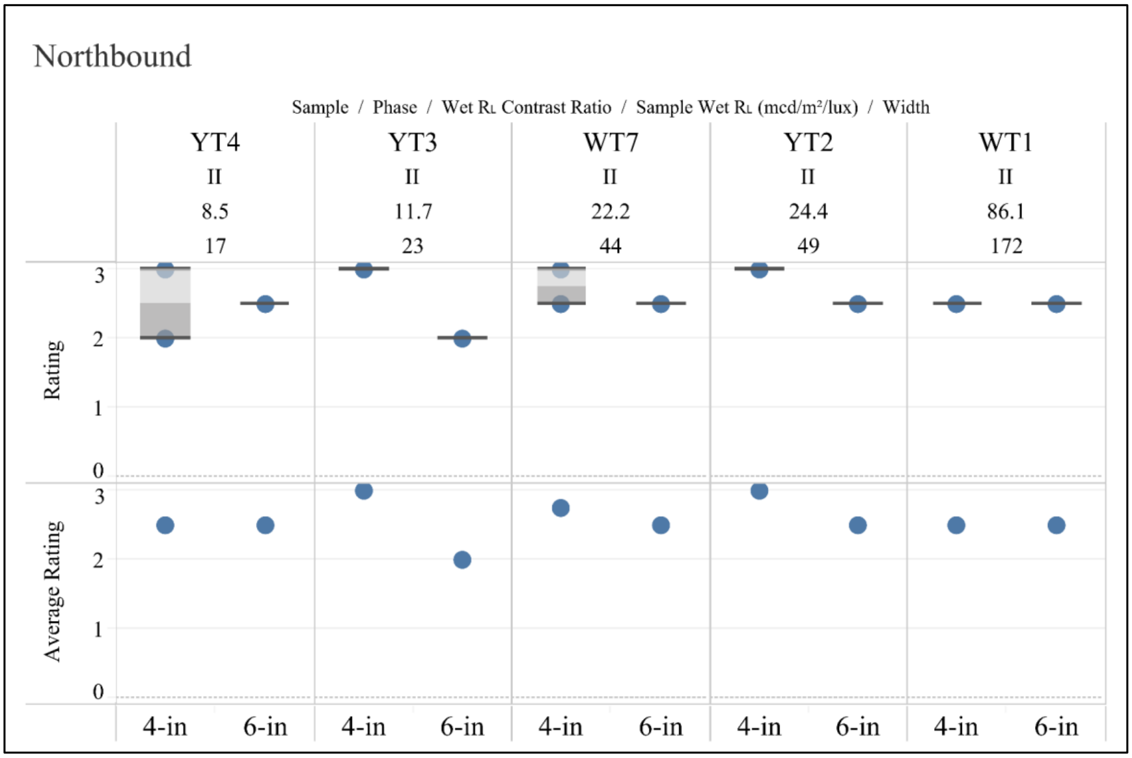


Figure 43. Wet, Nighttime, Glare Observations, 4- and 6-inch Phase II

The previously examined figures suggest that under the given test conditions, 4-inch markings perform similarly to 6-inch markings when considering the detection confidence rating from the MV system across a range of pavement marking qualities. It is important to realize that the confidence rating of all of the markings were typically of adequate level (greater than 2). The one test condition with consistent results was the wet daytime evaluation where the 6-inch markings generally had higher detection confidence levels.

The preceding figures have been summarized in Table 12 through Table 14. The tables present the percent change in the average detection confidence rating for each of the samples that occurred as a result of increasing the width of the markings from 4 to 6-inches.

Table 15 presents the average percent change in the ratings for each sample attributable to the test vehicle. The MV detection confidence ratings from the F-150 were compared to the ratings from the Explorer.

Table 12. Percent Change, Phase I 4-inch and Phase II 6-inch Relative to Phase II 4-inch

Daytime, dry				
	NB		SB	
Sample	Phase I 4-in	6-in	Phase I 4-in	6-in
WT1	8.0%	0.0%	-10.0%	-16.7%
WT7	24.4%	-11.1%	-8.0%	0.0%
YT2	10.0%	0.0%	18.8%	12.5%
YT3	10.0%	0.0%	18.8%	0.0%
YT4	0.0%	-10.0%	0.0%	-11.1%
Daytime, wet				
	NB		SB	
Sample	Phase I 4-in	6-in	Phase I 4-in	6-in
WT1	25.0%	16.7%	5.9%	-11.8%
WT7	15.0%	8.3%	-100.0%	0.0%
YT2	20.6%	3.7%	-14.3%	7.2%
YT3	5.6%	11.1%	11.1%	11.1%
YT4	4.4%	6.7%	0.0%	0.0%
Nighttime, dry				
	NB		SB	
Sample	Phase I 4-in	6-in	Phase I 4-in	6-in
WT1	0.0%	-25.0%	-16.7%	-8.3%
WT7	20.0%	0.0%	9.1%	9.1%
YT2	0.0%	-8.3%	-9.1%	0.0%
YT3	0.0%	0.0%	20.0%	0.0%
YT4	9.1%	0.0%	9.1%	-9.1%
Nighttime, wet				
	NB		SB	
Sample	Phase I 4-in	6-in	Phase I 4-in	6-in
WT1	5.9%	-11.8%	0.0%	-8.3%
WT7	20.0%	0.0%	20.0%	0.0%
YT2	-1.6%	12.5%	9.1%	0.0%
YT3	-5.6%	-16.7%	0.0%	-9.1%
YT4	-2.9%	1.5%	0.0%	-8.3%

Table 13. Percent Change, Phase II 6-inch Relative to Phase I 4-inch

Daytime, dry		
Sample	NB	SB
YT1	0.0%	-50.0%
WT6	-28.6%	-9.1%
WT3	-29.2%	0.0%
Daytime, wet		
Sample	NB	SB
YT1	-	-
WT6	11.1%	Infinite
WT3	-	-
Nighttime, dry		
Sample	NB	SB
YT1	-11.1%	0.0%
WT6	-3.0%	-16.7%
WT3	-10.0%	16.7%
Nighttime, wet		
Sample	NB	SB
YT1	-	-
WT6	7.9%	0.0%
WT3	-	-
(-) Indicates insufficient data to compare conditions		

Table 14. Percent Change, Phase II 6-inch Relative to Phase II 4-inch, Glare Conditions

	Dry	**Wet**
Sample	6-in	6-in
WT1	-16.7%	0.0%
WT7	-9.1%	-9.1%
YT2	-16.7%	-16.7%
YT3	0.0%	-33.3%
YT4	0.0%	0.0%

Table 15. Percent Change, F-150 Relative to Explorer, Phase II 4- and 6-inch Samples

Daytime, dry				
	Northbound		Southbound	
Sample	4-in	6-in	4-in	6-in
WT1	-7.3%	-12.9%	-15.6%	-2.4%
WT7	-11.1%	-0.5%	5.0%	2.1%
YT2	-0.2%	4.5%	19.9%	-10.3%
YT3	-11.0%	-10.3%	8.5%	12.5%
YT4	-14.5%	-10.3%	-8.4%	-9.9%
Nighttime, dry				
	Northbound		Southbound	
Sample	4-in	6-in	4-in	6-in
WT1	-23.9%	-11.1%	-5.4%	-1.7%
WT7	1.5%	8.7%	-7.9%	-10.7%
YT2	-13.5%	-5.4%	-12.4%	-8.2%
YT3	-19.4%	-7.8%	-22.9%	-16.9%
YT4	-8.8%	-6.9%	-11.8%	8.7%

T-Test Evaluation

The side-by-side comparisons of the ratings for various pavement markings provide substantial insight as to how well MV detects 6-inch wide longitudinal pavement markings relative to 4-inch wide markings while keeping all (or nearly all, in the case of three longitudinal pavement markings) sample properties constant. The three longitudinal pavement markings that were investigated as 6-inch markings only during the Phase II data collection period introduce the possibility that the sun position may affect the performance of the pavement markings, and were thus assessed separately. To confirm what was observed from the visual assessment, a series of two-sided T-tests, which determine if there is a significant difference between the means of two groups (i.e., if 6-inch markings perform significantly better or worse than 4-inch markings), was conducted for every sample and condition combination for which the markings were observed at both 4- and 6-inch widths. T-tests are conducted under the assumption that the variances of two populations are equal. This assumption allows for the calculation of the pooled variance, s_p^2, given by the following equation:

$$s_p^2 = \frac{(n_1-1)s_1^2+(n_2-1)s_2^2}{n_1+n_2-2}, \qquad [1]$$

Where s_1 is the sample variance obtained from a sample of size n_1, and s_2 is the sample variance obtained from a sample of size n_2. Using this pooled variance, a test statistic, t^*, is calculated by the following equation:

$$t^* = \frac{(\overline{X}_1-\overline{X}_2)-(\mu_1-\mu_2)}{\sqrt{s_p^2\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}}, \qquad [2]$$

Where and $(\mu_1 - \mu_2)$ is the difference between population means μ_1 and μ_2 under the null hypothesis while the term $(\overline{X}_1 - \overline{X}_2)$ is the observed difference between the sample means $\overline{X}_1$ and $\overline{X}_2$. The degrees of freedom of the test statistic in Equation 2 are $n_1 + n_2 - 2$, which are the degrees of freedom associated with the pooled variance s_p^2. To assess whether any statistically significant difference exists between the two groups, a (1-α)100 percent confidence interval (CI) for the difference between two population means $(\mu_1 - \mu_2)$ can be estimated based on a t distribution with $n_1 + n_2 - 2$ degrees of freedom using the following equation:

$$(\overline{X}_1-\overline{X}_2) \pm t_{\alpha/2}\sqrt{s_p^2\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}, \qquad [3]$$

Where α is the significance level [15]. For the purpose of this analysis, α was set at 0.05, resulting in the calculation of a 95 percent confidence interval for the true difference in the means of the two populations, specifically, the difference in detection confidence ratings assigned by the MV system to the 4-inch and 6-inch markings for each sample. The results of these T-tests are summarized in Table 16 through Table 19. When the value in the difference column is negative, the 6-inch sample was rated higher than the 4-inch version of the same sample. In addition to the values previously described, each table also includes a p-value that is indicative of the probability that the true difference in the population means exceeds the magnitude observed from the samples. It is fairly common practice that when p-value is smaller than the value of α, the null hypothesis of the markings performing the same regardless of width can be rejected, however, p-value is largely dependent on sample size, so it is important to consider the magnitude of the difference between the two groups and the practical implications of the difference when interpreting the results.

Table 16 provides the t-test results of the daytime dry conditions. Samples WT1, YT2, and WT7, performed better as 6-inch markings than as 4-inch markings. WT1, YT2, and WT7 consistently exhibited larger contrast ratios of CIE Y, Qd, and luminance in comparison to samples YT3 and YT4. Conversely, longitudinal pavement markings YT1, YT3, YT4, WT3, and WT6 performed better as 4-inch markings. The results for markings YT1, and WT6 are potentially attributable to the fact that these markings were collected as 4-inch markings during Phase I only. The largest discrepancy in the performance of markings during daytime dry conditions was observed for sample YT1, which performed very poorly as a 6-inch marking. Sample YT1, a yellow tape with Y contrast ratio of 0.88 during Phase I and 0.61 during Phase II and Qd contrast ratio of 1.30 northbound and 1.35 southbound for both Phases was the marking with the lowest performance characteristics.

Table 16. Daytime Dry T-Test Results

Sample	Difference	4-in mean	6-in mean	T-Stat	p-Value	DF	95% CI High	95% CI Low
WT1	-0.06	2.5	2.56	-0.53	0.61	18	-0.14	0.02
WT3	0.40	2.5	2.10	2.78	*0.01*	24	0.10	0.70
WT6	0.38	2.5	2.13	2.53	*0.02*	30	0.07	0.68
WT7	-0.04	2.33	2.38	-0.27	0.79	18	-0.36	0.28
YT1	0.48	1.0	0.53	1.46	0.16	24	-0.20	1.15
YT2	-0.13	2.38	2.50	-1.13	0.27	18	-0.36	0.11
YT3	0.17	2.29	2.13	1.47	0.16	18	-0.07	0.40
YT4	0.21	2.33	2.13	1.90	0.07	18	-0.02	0.44

Table 17 provides the t-test results of the daytime wet conditions. Generally speaking, the preformed tape pavement markings performed better under daytime wet conditions as 6-inch markings in comparison to 4-inch markings, with sample WT1 being the only exception. This observation is particularly interesting given that sample WT1 once again had the highest ratios of Y, Qd, and luminance among the samples. The potential exists that these samples experienced more puddling than the other types. Conversely the 4-inch marking may have high enough performance that the confidence rating could not be bettered by increasing marking width. The lower result with the 6-inch wide markings could be the result of other factors that were not able to be capture.

Table 17. Daytime Wet T-Test Results

Sample	Difference	4-in mean	6-in mean	T-Stat	p-Value	DF	95% CI High	95% CI Low
WT1	0.10	2.5	2.4	0.41	0.69	8	-0.46	0.66
WT6	-0.30	2.0	2.3	-0.80	0.43	20	-1.08	0.48
WT7	-0.05	2.25	2.3	-0.19	0.85	7	-0.66	0.56
YT2	-0.10	2.3	2.4	-0.63	0.54	8	-0.46	0.26
YT3	-0.25	2.25	2.5	-1.97	0.09	7	-0.55	0.05
YT4	-0.15	2.25	2.4	-0.59	0.57	9	-0.72	0.42

Table 18 presents the nighttime dry condition t-test results. Samples WT7, YT1, and YT3 performed better as 6-inch markings while the remaining samples performed better as 4-inch markings. With the exception of marking YT1 the markings all performed very well as 4-inch markings. Despite performing slightly better as a 6-inch marking, marking YT1 was still the worst performing marking for this scenario. The marking had an R_L contrast ratio of 1.57 northbound and 1.66 southbound as a six-inch marking during Phase II, and an R_L contrast ratio of 2.29 northbound and 2.31 southbound as a 4-inch marking during Phase I. Interestingly, marking WT6 also had R_L contrast ratios that were similarly low but performed much better. This may suggest that R_L may not be the most appropriate performance measure for determining marking detectability by the MV system used in this study.

Table 18. Nighttime Dry T-Test Results

Sample	Difference	4-in mean	6-in mean	T-Stat	p-Value	DF	95% CI High	95% CI Low
WT1	0.44	2.94	2.50	3.86	0	14	0.19	0.68
WT3	0.13	2.50	2.38	0.65	0.52	20	-0.28	0.53
WT6	0.20	2.70	2.5	1.22	0.24	18	-0.14	0.54
WT7	-0.06	2.69	2.75	-0.48	0.64	14	-0.34	0.22
YT1	-0.15	0.75	0.90	-0.73	0.48	19	-0.58	0.28
YT2	0.19	2.81	2.63	1.53	0.15	14	-0.08	0.45
YT3	-0.06	2.69	2.75	-0.48	0.64	14	-0.34	0.22
YT4	0.13	2.81	2.69	0.97	0.35	14	-0.15	0.40

Table 19 presents the nighttime wet condition t-test results. Samples WT6 and YT2 perform better as 6-inch marking while the remaining samples performed better as 4-inch markings. All of the markings 4 or 6-inch performed well.

The results of the t-tests support the findings from the graphical analysis that indicate that 6-inch markings are most beneficial under daytime, wet conditions.

Table 19. Nighttime Wet T-Test Results

Sample	Difference	4-in mean	6-in mean	T-Stat	p-Value	DF	95% CI High	95% CI Low
WT1	0.3	2.9	2.6	2.12	0.07	8	-0.03	0.63
WT6	-0.2	2.7	2.9	-1.15	0.27	13	-0.57	0.17
WT7	0.12	2.7	2.58	0.81	0.44	9	-0.21	0.44
YT2	-0.2	2.7	2.9	-1.26	0.24	8	-0.56	0.16
YT3	0.3	2.8	2.5	2.71	*0.02*	9	0.05	0.55
YT4	0.05	2.8	2.75	0.3	0.77	9	-0.33	0.43

CHAPTER 4. FINDINGS, RECOMMENDATIONS, AND SUGGESTED RESEARCH

FINDINGS

The results of the research show that 6-inch wide preformed tape pavement markings provide higher levels of detection confidence, for the LDW ADAS tested, in some but not all scenarios compared to 4-inch wide markings. In dry daytime and nighttime conditions with 4-inch wide markings in a good state of repair (i.e., markings with retroreflectivity, color, and contrast levels that would generally be deemed adequate by today's practices or standards), the performance of MV LDW system was high; and in these cases the increased width of 6-inch markings had no measurable impact. The research showed that 6-inch wide markings improve MV LDW performance when the detection of 4-inch markings was more difficult. In particular, wet daytime conditions were found to be a challenge for MV LDW pavement marking detection. In this case, 6-inch markings consistently improved the MV LDW pavement marking detection performance. The MV LDW performance in wet nighttime was consistently better than in wet daytime conditions, which was unexpected but possibly caused by the vertical profile of the pavement marking tape used to conduct this study. The pavement marking tape was manufactured with various levels of retroreflectivity and shades of white and yellow. The intent was to have the ability to control these factors in a uniform and repeatable way. However, this approach also led to inherent limitations. As described, the pavement marking tape included a profiled design, which provides a way for the markings to drain quicker than a more typical flat marking (the vast majority of markings in the US are flat markings, with no vertical profile). Also, the tape provided well-defined longitudinal edges that represent newly installed markings and not markings that have been in the field for any considerable length of time (pavement markings wear from the top and also the edges, leading to in-service markings less than 4-inches wide and also having inconsistent edges). This may have also led to some limitations in this study since MV LDW systems generally look for sharp edges of longitudinal contrast differential as a primary method for detecting pavement markings.

Parallel and on-going research has also been underway to evaluate the characteristics of pavement markings that affect MV LDW detectability (NCHRP 20-102(6)). The NCHRP study also showed that wet daytime conditions were a challenge for MV ADAS performance. In addition, the NCHRP study also identified other scenarios where MV ADAS performance may benefit from 6-inch wide pavement markings. For instance, it was found that higher speeds and lower contrast reduced MV LDW detectability of 4-inch markings. It was also found that lane line markings had lower detection confidence levels than comparable edge line markings. Glare was also shown to reduce the MV LDW performance (daytime and nighttime). Based on the study results obtained for the current work, these are examples of other conditions where 6-inch wide pavement markings can improve MV LDW performance. Other conditions where 6-inch wide longitudinal pavement markings may potentially improve MV detection performance as compared to 4-inch wide markings are the following areas where potentially conflicting signals may confuse MV systems from detecting and tracking the markings: areas with remnants of previously removed markings, pavement scarring due to removal activities, blackout markings, crack seal, longitudinal seams in the pavement, varying road surfaces, cracking, rutting, or areas where glare is common and impacts marking visibility.

The impact of pavement marking width was not consistent across all test scenarios. There are several reasons why the width of the marking may not have had a consistent impact on the confidence rating from the ADAS MV system. These reasons include the following:

Markings

- The markings evaluated were preformed tape markings with a uniform appearance and well-defined edges. Typical worn markings at the colors and retroreflectivity levels evaluated would likely not be as consistent. The biggest benefit of 6-inch wide markings may be when the markings are physically worn and lose their uniform appearance.
- The 4-inch markings generally provided high confidence levels.
- The markings evaluated as both 4 and 6-inch markings during the same phase were all a profiled tape material. The profile is beneficial when water is present as a portion of the marking remains above the water, in contrast to flat tape and liquid markings.

MV System

- The MV system used in this study focuses on pavement markings located 30-50 feet in front of the vehicle and therefore may not be looking far enough down the road to see benefits of the additional pavement marking width across all evaluation scenarios. 6-inch wide markings due to their increased target size will be more visible at greater distances than 4-inch wide markings.
- The 0 to 3 whole value confidence output leaves little room for varying levels of confidence when sample properties are slightly changed. For the given test conditions, the contrast levels of the preformed tape pavement markings were adequate for MV detection regardless of the width.

Roadway

- The road surface was fairly consistent allowing the system to possibly detect the markings easier than if the road surface had conflicting signals near the markings.
- The testing was only conducted in straight tangent sections with continuous markings (additional testing on broken lane line markings was conducted as a part of NCHRP 20-102 (6)).

RECOMMENDATIONS

This research shows that 6-inch wide longitudinal markings consistently improved MV detection performance under wet daytime conditions, which is critical since this has proven to be a difficult conditions for pavement marking detection with the MV technologies tested. Combined with results from the on-going NCHRP 20-102 (06) research, 6-inch wide lane line markings can also be expected to improve MV detection performance as vehicle speed increases (based on testing at speeds of 40, 55, and 65 mph). Other conditions where 6-inch wide longitudinal pavement markings may potentially improve MV detection performance as compared to 4-inch wide markings are the following areas where potentially conflicting signals may confuse MV systems from detecting and tracking the markings: areas with remnants of previously removed markings, pavement scarring due to removal activities, blackout markings, crack seal, longitudinal seams in the pavement, varying road surfaces, cracking, rutting, or areas where glare is common and impacts marking visibility.

The researchers recommend that additional research be conducted as outlined in the suggest research section below to gather additional information on the impact of 6-inch wide pavement markings on detectability by MV systems. In the interim, the researchers recommend that 6-inch wide markings be considered in broken lane line areas with speeds of 65 mph or greater. Based on the on-going NCHRP 20-102 (06) study, observations taken at 65 mph tended to have lower MV confidence ratings than those taken at 50 mph, and broken lane line areas showed lower detection confidence levels than edge line markings. 6-inch wide markings (edge line, center line, lane line) should be considered in areas where run-off-the-road crashes are common. The research presented herein shows benefits to the MV system and literature shows improved safety for human drivers when 6-inch wide markings are implemented. The researchers recommend that 6-inch wide markings be considered in areas where rain and wet conditions are common. The researchers also recommend 6-inch wide markings be considered in areas where conflicting signals may confuse MV systems from detecting the markings, i.e. areas with previously removed markings, blackout markings, crack seal, varying road surfaces, cracking, rutting, or glare.

This research is unable to provide estimates of the costs or safety impacts based on the recommendations. Lack of information on the quantity of markings that may benefit if upgraded and lack of safety information on ADAS technologies (especially related to 4-inch vs 6-inch wide marking improvements) limit the researchers' ability to provide a confident estimate. Historic cost and safety implications will see greater benefit when considering the benefits to ADAS technology, as both the human driver and ADAS technologies will see benefits of implementing 6-inch wide markings.

The on-going NCHRP 20-102 (06) study provided a prioritized list of pavement marking characteristics that were deemed most important for current MV systems based on available testing and knowledge. The research presented in this report comparing MV detection of 4-inch and 6-inch markings supports that list of marking characteristics. The list is provided below, additional details are provided in the NCHRP report.

1. Pavement marking presence
2. Contrast ratio between the marking and road surface
    a. Daytime marking characteristics (i.e., CIE Y or Qd)
    b. Nighttime marking characteristics (i.e., R_L)
3. Pavement marking width
4. Wet-weather characteristics
5. Lane line pattern
6. Marking texture/structure

The research on the MV system evaluated indicates that the camera sees similarly to a human, but human interpretation of the scene and the MV algorithm interpretation of the scene may differ. Both the human driver and the MV system detection of markings decreases if conflicting signals are present. MV systems may be more susceptible than human drivers to conflicting signals due to limitations of the algorithms used to process the scene. Pavement marking practices should provide markings in a good state of repair without other signals that could be mistaken for longitudinal delineation. In addition, both the human driver and the MV system detection of markings decreases if glare signals are present. This glare can be from the sun, oncoming headlights, or other light sources at night. Methods to mitigate the impacts of glare need to be developed to benefit both the human driver and MV systems. These methods could be related to the pavement marking characteristics or to the MV system hardware or software. This research represents an important step in understanding the changing design needs for roadway infrastructure to accommodate the rapidly changing ADAS and AV technology used in modern automobiles.

STUDY LIMITATIONS

The scope of the study and the selected research approach resulted in several limitations that impact the results. These limitations need to be considered when evaluating the results and when developing future research that evaluates MV and the impact of pavement marking width on detection confidence.

- The scope of the work did not allow for several factors to be explored in-depth. Glare from the sun and an oncoming vehicle were only partially examined. Profiled tape samples were part of the markings studied but the impact of the profile pattern was not specifically evaluated. Broken lane line markings and contrast markings were not evaluated as part of this work.
- Despite efforts to engage with several MV providers, only one MV system was used in the study.
- The closed course study approach limited the ability to evaluate naturally aged markings. The markings evaluated had various levels of retroreflectivity and color representing different levels of worn markings, but they still had 100 percent presence and well-defined edges.
- All of the testing was performance on a concrete road surface.
- The visual appearance of the road surface was consistent allowing the system to possibly detect the markings easier than if the road surface was more variable in appearance or if conflicting signals were present near the markings.
- The testing was only conducted in straight tangent sections.

SUGGESTED RESEARCH

Additional research is needed to ensure that road agencies and suppliers/manufacturers of pavement markings are well equipped to provide and maintain markings that are easily recognizable by MV systems. Additional research should build upon this work by addressing the limitations described above. Additional research topics should include the following:

- Future research should investigate other MV based ADAS technologies to determine the effect of pavement marking width on the reliability of their performance. Research in this area should examine systems which look further down the roadway and may see greater benefit from 6-inch wide markings, which are intended to improve visibility at greater distances. Systems capable of detecting pavement markings at varying distances (instead of within a fixed viewing window) may also be of interest.
- Additional research should explore the impacts of worn markings more representative of in-service markings—specifically in terms of the markings being flat with worn edges (paint and thermoplastic make up the vast majority of pavement marking materials in the US).

- Future studies should assess a variety of pavement types to develop a more robust understanding of the effect of pavement marking width in conjunction with varying marking properties (color and retroreflectivity) and the resulting contrast between the marking and darker or lighter colored pavements. Research in this area could aim to examine at what pavement color, whether due to the material itself or weathering, contrast markings become beneficial.
- Future research could also examine whether wider markings (8 or more inches in width) have a more pronounced benefit compared to 4 or 6-inch wide markings. Future research should specifically evaluate marking width and the impact of contrast markings and lane line markings.
- Additional research is needed to better understand the effects of glare from the sun, glare at night, and rainy conditions to determine if 6-inch wide markings can be used to help mitigate the detrimental impacts of the glare and rain. It is possible that marking width would have a more dramatic effect on MV performance in situations were conflicting signals may make it more difficult to determine what is the marking and what is a false signal. Testing should be conducted in areas with conflicting signals to determine if 6-inch wide markings are beneficial. These areas could include areas with remnants of previously removed markings, pavement scarring due to removal activities, blackout markings, crack seal, longitudinal seams in the pavement, varying road surfaces, cracking, rutting, or areas where glare is common and impacts marking visibility.
- Evaluation of lower visibility markings. During this study, most of the markings performed well regardless of contrast ratio. Future research should investigate the minimum contrast needed for MV detection and the role of marking width in detection at low visibility levels. The research should again consider a variety of materials, including tape, paint, and thermoplastic, to assess if the material type plays a role in detectability.

Beyond the suggested research topics, continued effort is needed to promote and support an open dialogue, between the various groups that are affected by these new technologies. Agencies and industry on the infrastructure side and suppliers and OEMs on the MV side. Industry groups such as ATSSA, ASC, and SAE can help bridge the gap between government and industry to improve collaboration and advancement of these technologies.

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APPENDIX A: SUMMARY OF SAMPLE PROPERTIES

TABULAR SAMPLE SUMMARY

MiniScan Observations, Phase I

Sample	Color	Marking Y	Pavement Y	Ratio	x	y
WT1	White	64	13	4.8	0.3178	0.3400
WT3	W	28	16	1.7	0.3229	0.3400
WT6	White	47	16	2.9	0.3177	0.3400
WT7	White	48	13	3.8	0.3183	0.3400
YT1	Yellow	13	15	0.9	0.3545	0.3700
YT2	Yellow	37	15	2.5	0.4799	0.4300
YT3	Yellow	32	12	2.8	0.4612	0.4300
YT4	Yellow	31	14	2.2	0.4602	0.4300

MiniScan Observations, Phase II

Sample	Color	Marking Y	Pavement Y	Ratio	x	y
WT1	White	63	14	4.4	0.3180	0.3400
WT3	White	24	14	1.7	0.3105	0.3300
WT6	White	47	17	2.7	0.3181	0.3400
WT7	White	50	16	3.1	0.3191	0.3400
YT1	Yellow	10	17	0.6	0.3416	0.3600
YT2	Yellow	38	15	2.6	0.4872	0.4300
YT3	Yellow	35	16	2.2	0.4705	0.4300
YT4	Yellow	30	13	2.4	0.4665	0.4300

Delta LTL-XL Measurements, Phase I

Sample	Direction	Qd		
		Marking (mcd/m^2/lux)	Pavement (mcd/m^2/lux)	Ratio
WT1	NB	227	58	3.9
WT3	NB	137	55	2.5
WT6	NB	125	70	1.8
WT7	NB	128	59	2.2
YT1	NB	85	66	1.3
YT2	NB	125	55	2.3
YT3	NB	99	59	1.7
YT4	NB	90	50	1.8
WT1	SB	243	53	4.6
WT3	SB	135	52	2.6
WT6	SB	128	66	1.9
WT7	SB	126	55	2.3
YT1	SB	85	63	1.4
YT2	SB	128	52	2.5
YT3	SB	102	59	1.7
YT4	SB	91	49	1.9

Delta LTL-XL Measurements, Phase II

Sample	Direction	Qd		
		Marking (mcd/m^2/lux)	Pavement (mcd/m^2/lux)	Ratio
WT1	NB	249	65	3.9
WT3	NB	132	60	2.2
WT6	NB	131	72	1.8
WT7	NB	127	71	1.8
YT1	NB	91	70	1.3
YT2	NB	136	63	2.2
YT3	NB	120	69	1.7
YT4	NB	95	55	1.7
WT1	SB	248	65	3.8
WT3	SB	119	55	2.2
WT6	SB	133	69	1.9
WT7	SB	127	68	1.9
YT1	SB	89	66	1.4
YT2	SB	136	63	2.2
YT3	SB	119	68	1.8
YT4	SB	93	55	1.7

Delta LTL-X Mark II Measurements, Phase I

Sample	Direction	R_L			Recovery R_L	
		Marking (mcd/m²/lux)	Pavement (mcd/m²/lux)	Ratio	Marking (mcd/m²/lux)	Ratio
WT1	NB	1021	13	75.9	100	49.8
WT3	NB	31	13	2.3	20	9.9
WT6	NB	24	17	1.4	16	7.9
WT7	NB	101	14	7.3	34	17.1
YT1	NB	33	14	2.3	1	0.3
YT2	NB	404	13	31.0	52	26.1
YT3	NB	100	14	7.3	17	8.5
YT4	NB	193	13	14.9	21	10.3
WT1	SB	931	12	76.5	100	49.8
WT3	SB	30	12	2.4	20	9.9
WT6	SB	23	15	1.6	16	7.9
WT7	SB	102	13	8.0	34	17.1
YT1	SB	33	14	2.3	1	0.3
YT2	SB	374	13	29.8	52	26.1
YT3	SB	86	13	6.6	17	8.5
YT4	SB	183	12	15.2	21	10.3

LTL-X Mark II Measurements, Phase II

Sample	Direction	R_L			Recovery R_L	
		Marking (mcd/m²/lux)	Pavement (mcd/m²/lux)	Ratio	Marking (mcd/m²/lux)	Ratio
WT1	NB	928	15	61.5	172	86.1
WT3	NB	45	16	2.8	33	16.3
WT6	NB	24	17	1.4	19	9.3
WT7	NB	88	17	5.2	44	22.2
YT1	NB	27	17	1.6	2	0.8
YT2	NB	466	17	28.1	49	24.4
YT3	NB	79	18	4.5	23	11.7
YT4	NB	197	15	12.8	17	8.5
WT1	SB	861	15	57.1	172	86.1
WT3	SB	48	16	3.1	33	16.3
WT6	SB	30	17	1.8	19	9.3
WT7	SB	92	17	5.4	44	22.2
YT1	SB	28	17	1.7	2	0.8
YT2	SB	474	17	28.6	49	24.4
YT3	SB	86	18	4.9	23	11.7
YT4	SB	201	15	13.1	17	8.5

Phase I Daytime Dry CCD Luminance Measurements

Sample	Color	Northbound			Southbound		
		Marking (cd/m^2)	Pavement (cd/m^2)	Ratio	Marking (cd/m^2)	Pavement (cd/m^2)	Ratio
WT1	White	12286	2217	5.5	7481	2246	3.3
WT3	White	4683	1887	2.5	7453	2880	2.6
WT6	White	5397	3215	1.7	3547	2655	1.3
WT7	White	6358	2659	2.4	4475	2479	1.8
YT1	Yellow	2253	2803	0.8	5385	2909	1.9
YT2	Yellow	6400	2033	3.2	3953	2403	1.6
YT3	Yellow	5065	1872	2.7	5159	2409	2.1
YT4	Yellow	4544	2419	1.9	4445	2215	2.0

Phase II Daytime Dry CCD Measurements

Sample	Color	Northbound			Southbound		
		Marking (cd/m^2)	Pavement (cd/m^2)	Ratio	Marking (cd/m^2)	Pavement (cd/m^2)	Ratio
WT1	White	16794	3226	5.2	13810	3141	4.4
WT3	White	5442	3420	1.6	5839	3302	1.8
WT6	White	6604	3450	1.9	5829	3482	1.7
WT7	White	7745	3513	2.2	7192	3853	1.9
YT1	Yellow	2580	3608	0.7	3092	3726	0.8
YT2	Yellow	8717	3107	2.8	7390	3738	2.0
YT3	Yellow	6767	3654	1.9	6765	4347	1.6
YT4	Yellow	5701	3233	1.8	5514	3328	1.7

Phase I Daytime Wet CCD Luminance Measurements

Sample	Color	Northbound			Southbound		
		Marking (cd/m^2)	Pavement (cd/m^2)	Ratio	Marking (cd/m^2)	Pavement (cd/m^2)	Ratio
WT1	White	2888	555	5.2	2102	744	2.8
WT3	White	479	1202	0.4	479	1202	0.4
WT6	White	3745	1564	2.4	3745	1564	2.4
WT7	White	3555	1080	3.3	3555	1080	3.3
YT1	Yellow	2415	2010	1.2	2415	2010	1.2
YT2	Yellow	1584	1399	1.1	1818	1821	1.0
YT3	Yellow	1716	1640	1.1	1716	1640	1.1
YT4	Yellow	1884	1464	1.3	1884	1464	1.3

Phase II Daytime Wet CCD Measurements

Sample	Color	Northbound			Southbound		
		Marking (cd/m^2)	Pavement (cd/m^2)	Ratio	Marking (cd/m^2)	Pavement (cd/m^2)	Ratio
WT1	White	13707	2810	4.9	12979	2455	5.3
WT3	White	4292	2146	2.0	5045	2045	2.5
WT6	White	3633	1553	2.3	3500	1735	2.0
WT7	White	4311	2194	2.0	4596	2204	2.1
YT1	Yellow	2436	2562	1.0	2243	2343	1.0
YT2	Yellow	7873	3810	2.1	7960	3341	2.4
YT3	Yellow	4466	3276	1.4	4688	3001	1.6
YT4	Yellow	4838	3536	1.4	5409	2952	1.8

Phase I Nighttime Dry CCD Luminance Measurements

Sample	Color	Northbound			Southbound		
		Marking (cd/m^2)	Pavement (cd/m^2)	Ratio	Marking (cd/m^2)	Pavement (cd/m^2)	Ratio
WT1	White	11.7	0.3	34.2	12.8	0.4	34.9
WT3	White	0.7	0.4	1.9	0.6	0.3	1.9
WT6	White	0.6	0.4	1.7	0.9	0.6	1.5
WT7	White	1.6	0.3	4.6	2.0	0.4	4.5
YT1	Yellow	0.5	0.5	1.1	0.4	0.4	0.9
YT2	Yellow	7.2	0.4	18.7	6.0	0.4	17.2
YT3	Yellow	2.2	0.5	4.2	1.6	0.4	4.5
YT4	Yellow	3.6	0.4	9.6	2.5	0.3	7.6

Phase II Nighttime Dry CCD Measurements

Sample	Color	Northbound			Southbound		
		Marking (cd/m^2)	Pavement (cd/m^2)	Ratio	Marking (cd/m^2)	Pavement (cd/m^2)	Ratio
WT1	White	12.0	0.3	41.3	13.8	0.4	35.8
WT3	White	0.5	0.3	1.9	0.8	0.4	2.3
WT6	White	0.7	0.3	2.2	0.7	0.4	1.6
WT7	White	1.1	0.3	3.8	1.5	0.4	3.8
YT1	Yellow	0.5	0.4	1.3	0.5	0.4	1.4
YT2	Yellow	8.9	0.3	28.2	6.3	0.4	16.4
YT3	Yellow	1.3	0.4	3.7	1.7	0.4	4.3
YT4	Yellow	3.4	0.3	11.5	3.4	0.3	10.6

Phase II Nighttime Wet CCD Measurements

Sample	Color	Northbound			Southbound		
		Marking (cd/m^2)	Pavement (cd/m^2)	Ratio	Marking (cd/m^2)	Pavement (cd/m^2)	Ratio
WT1	White	3.3	0.1	31.7	3.3	0.1	31.7
WT3	White	0.5	0.1	4.3	0.5	0.1	4.3
WT6	White	0.6	0.1	4.6	0.6	0.1	4.6
WT7	White	0.9	0.1	8.6	0.9	0.1	8.6
YT1	Yellow	0.1	0.1	1.6	0.1	0.1	1.6
YT2	Yellow	1.7	0.1	26.2	1.7	0.1	26.2
YT3	Yellow	0.6	0.1	11.9	0.6	0.1	11.9
YT4	Yellow	1.1	0.1	17.1	1.1	0.1	17.1

Phase II Nighttime Dry Glare CCD Measurements

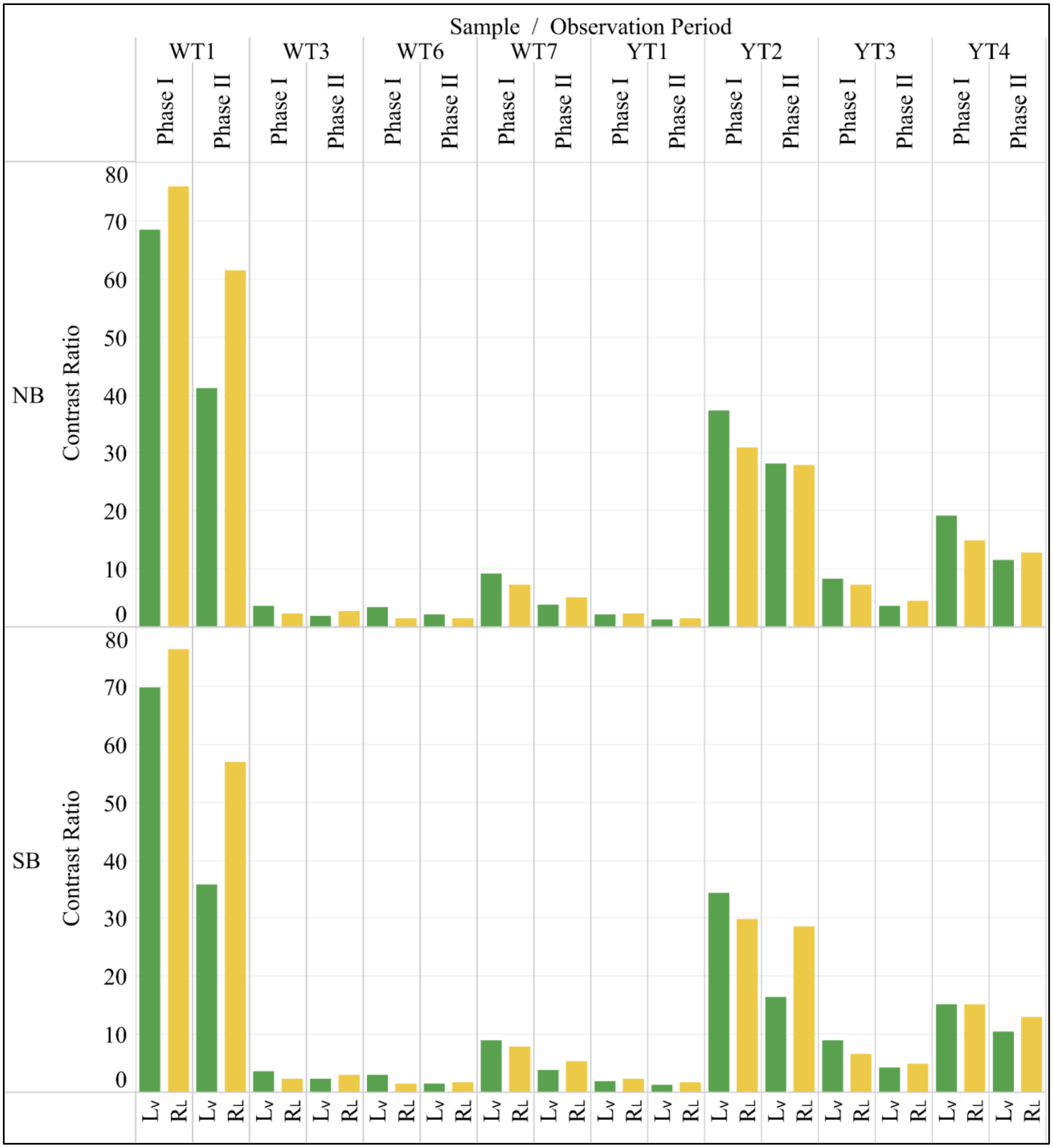
Sample	Color	Northbound			Southbound		
		Marking (mcd/m^2)	Pavement (mcd/m^2)	Ratio	Marking (mcd/m^2)	Pavement (mcd/m^2)	Ratio
WT1	White	-	-	-	-	-	-
WT3	White	-	-	-	-	-	-
WT6	White	0.7	0.3	2.1	-	-	-
WT7	White	1.1	0.3	3.5	-	-	-
YT1	Yellow	0.5	0.5	1.1	-	-	-
YT2	Yellow	-	-	-	-	-	-
YT3	Yellow	1.4	0.5	3.0	-	-	-
YT4	Yellow	-	-	-	-	-	-
The dash symbol (-) indicates no data available for a particular sample							

Phase II Nighttime Wet Glare CCD Measurements

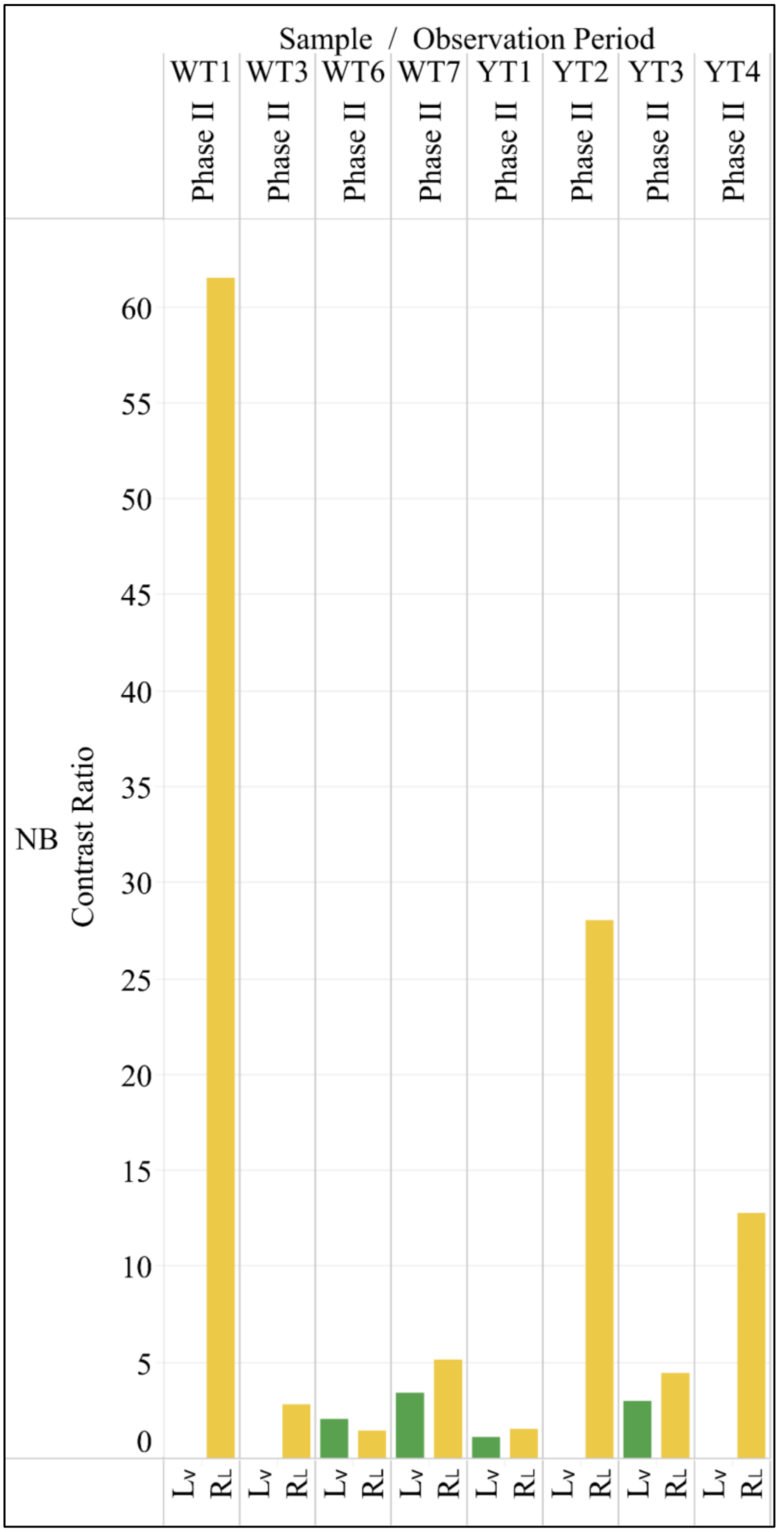
Sample	Color	Northbound			Southbound		
		Marking (mcd/m^2)	Pavement (mcd/m^2)	Ratio	Marking (mcd/m^2)	Pavement (mcd/m^2)	Ratio
WT1	White	7.8	0.2	47.4	-	-	-
WT3	White	0.5	0.2	3.2	-	-	-
WT6	White	0.6	0.2	3.5	-	-	-
WT7	White	1.0	0.1	7.2	-	-	-
YT1	Yellow	0.3	0.4	0.9	-	-	-
YT2	Yellow	2.6	0.2	11.0	-	-	-
YT3	Yellow	0.9	0.2	3.7	-	-	-
YT4	Yellow	1.6	0.3	5.8	-	-	-
The dash symbol (-) indicates no data available for a particular sample							

CONTRAST RATIO COMPARISONS

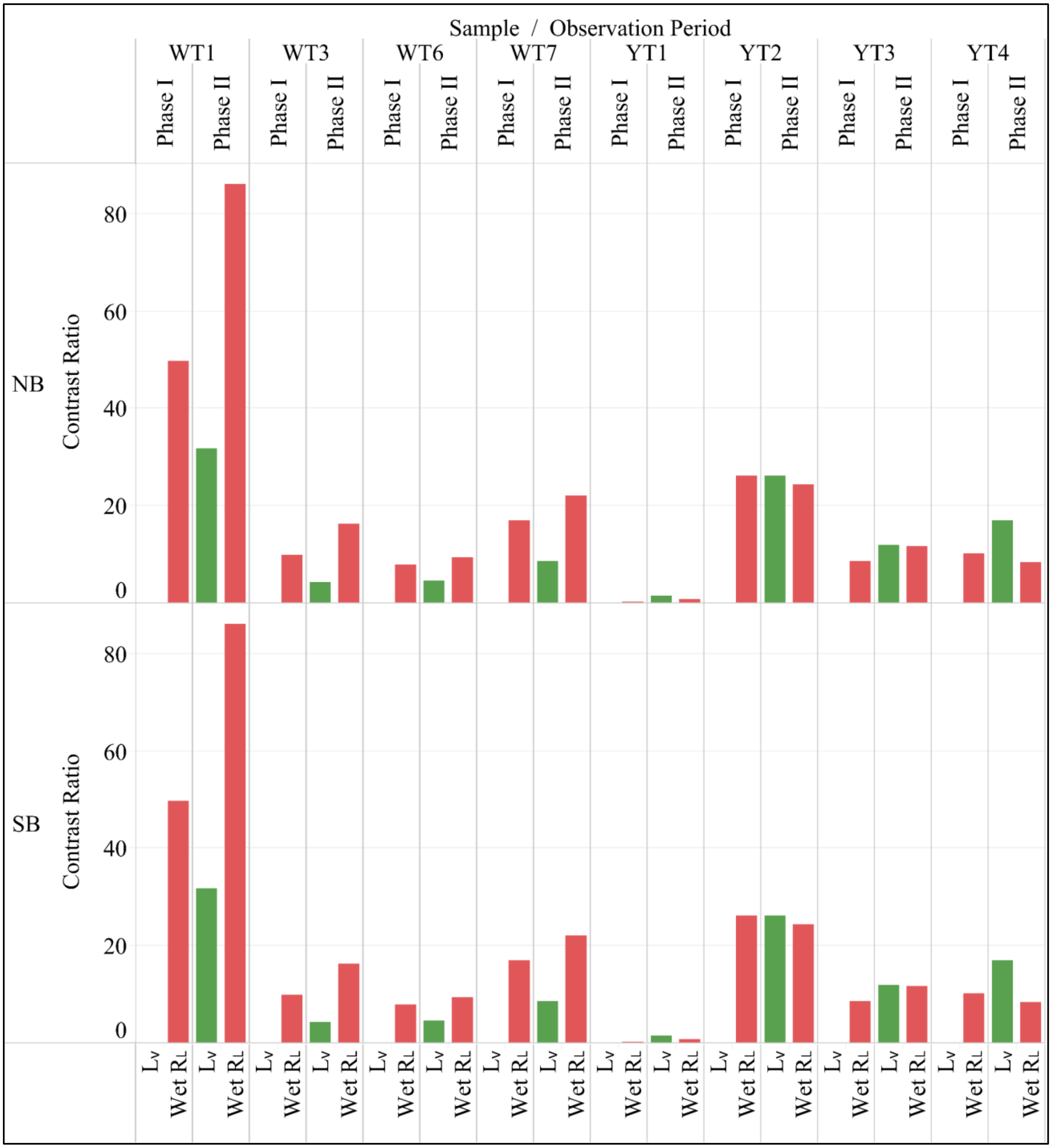
Wet, Daytime Contrast Ratios



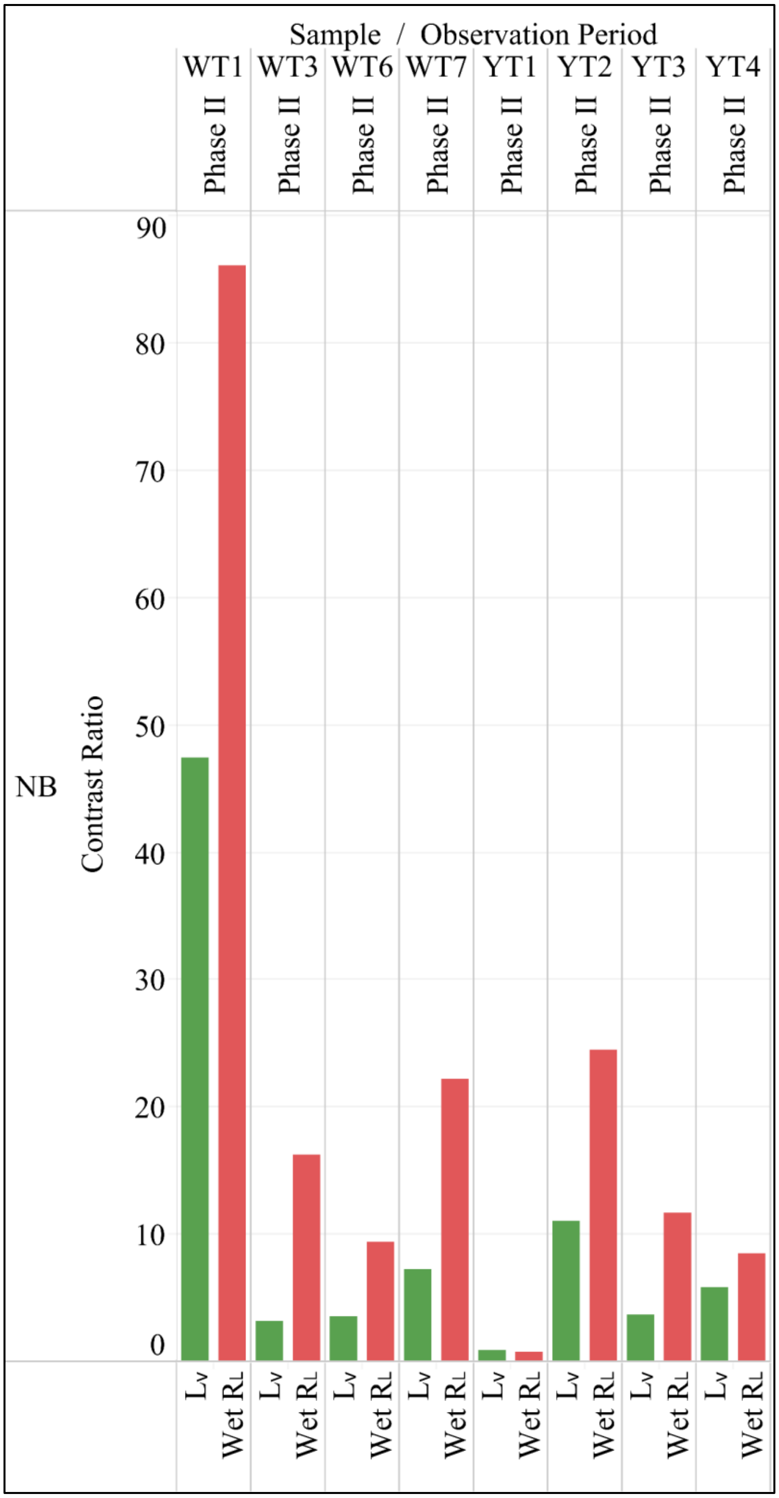
Dry, Nighttime Contrast Ratios



Dry, Nighttime with Glare Contrast Ratios



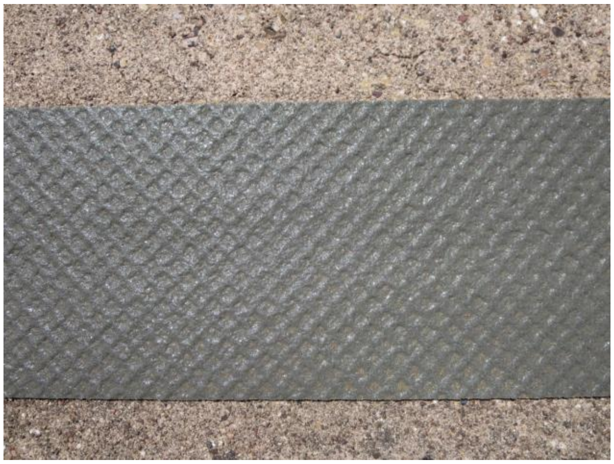
Wet, Nighttime Contrast Ratios



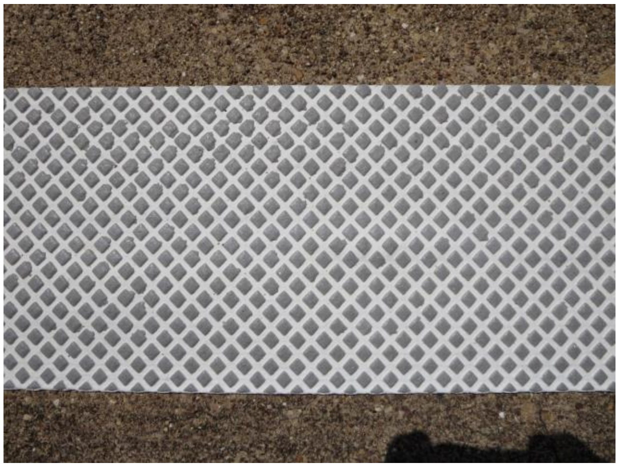
Wet, Nighttime with Glare Contrast Ratios

APPENDIX B: PAVEMENT MARKINGS

Phase II Marking Section 1-Samples YT1 [L] and WT6 [R]

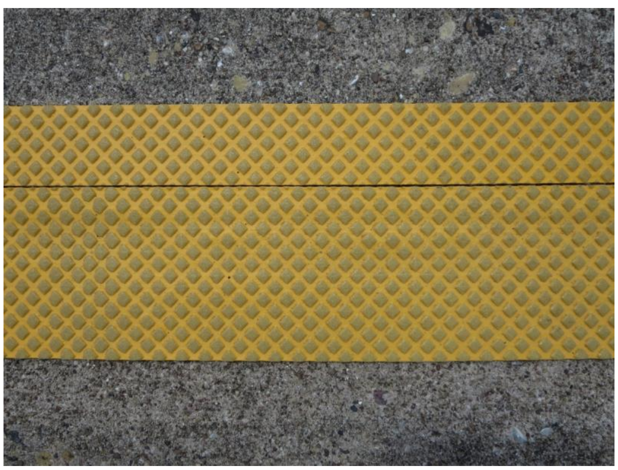


Sample YT1

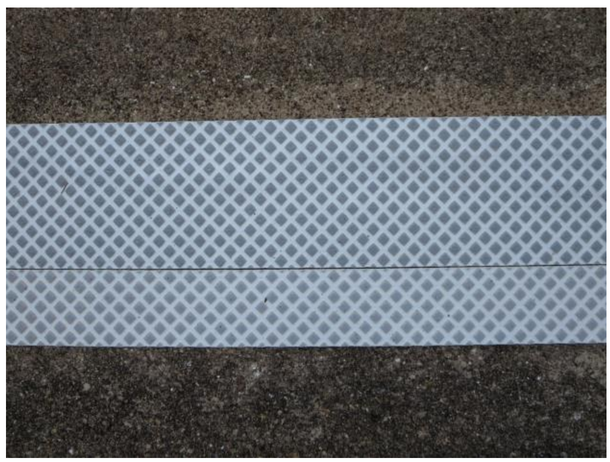


Sample WT6

Phase II Marking Section 2-Samples YT3 [L] and WT7 [R]



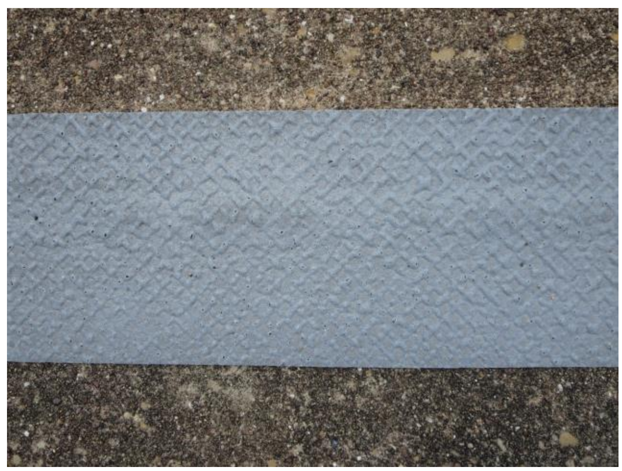
Sample YT3



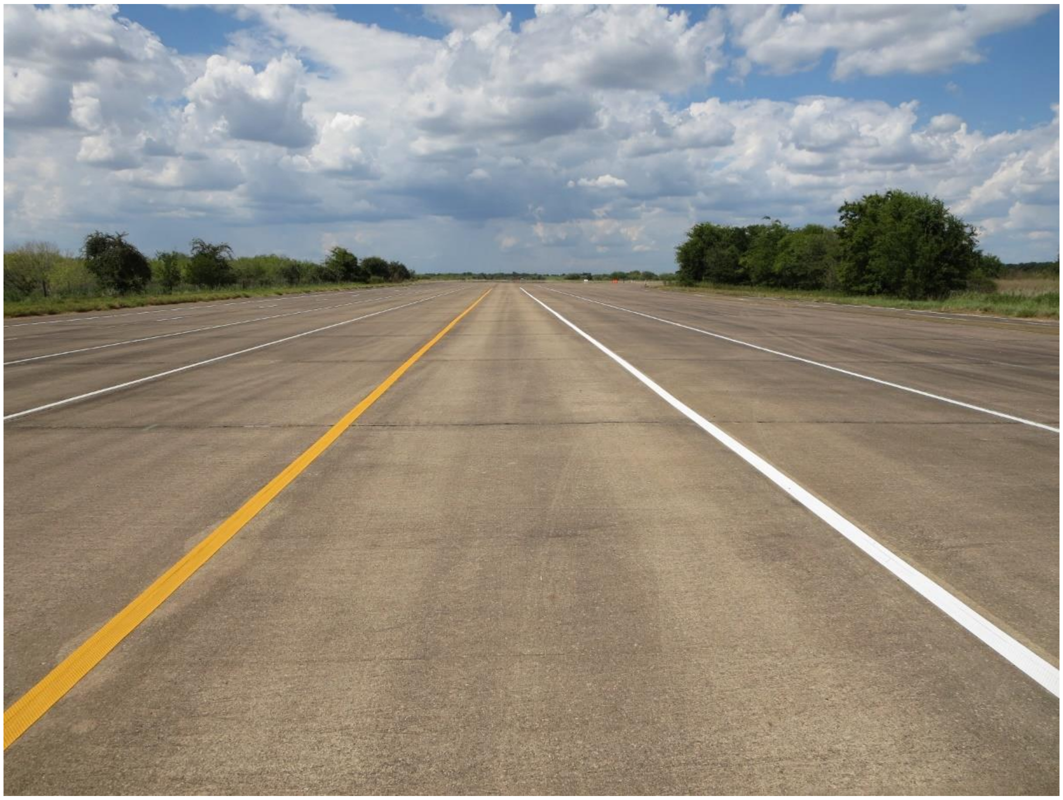
Sample WT7

Phase II Marking Section 3-Samples YT4 [L] and WT3 [R]

Sample YT4

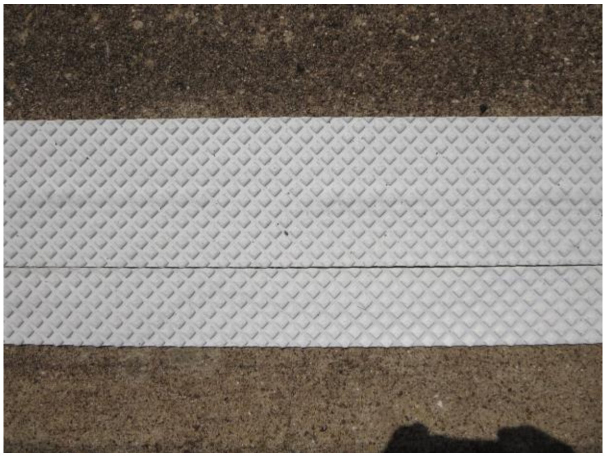


Sample WT3



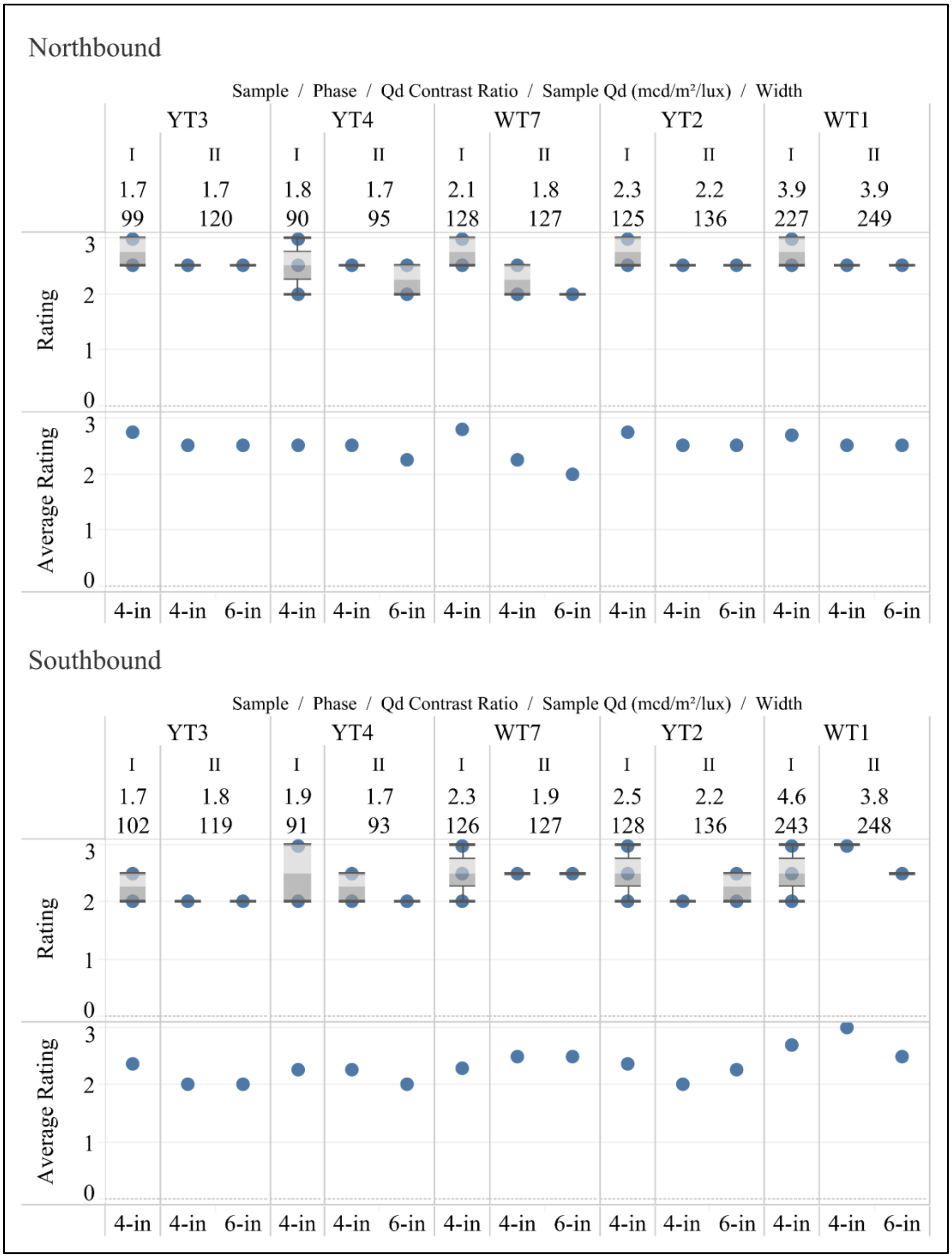
Phase II Marking Section 4-Samples YT2 [L] and WT1 [R]

Sample YT2

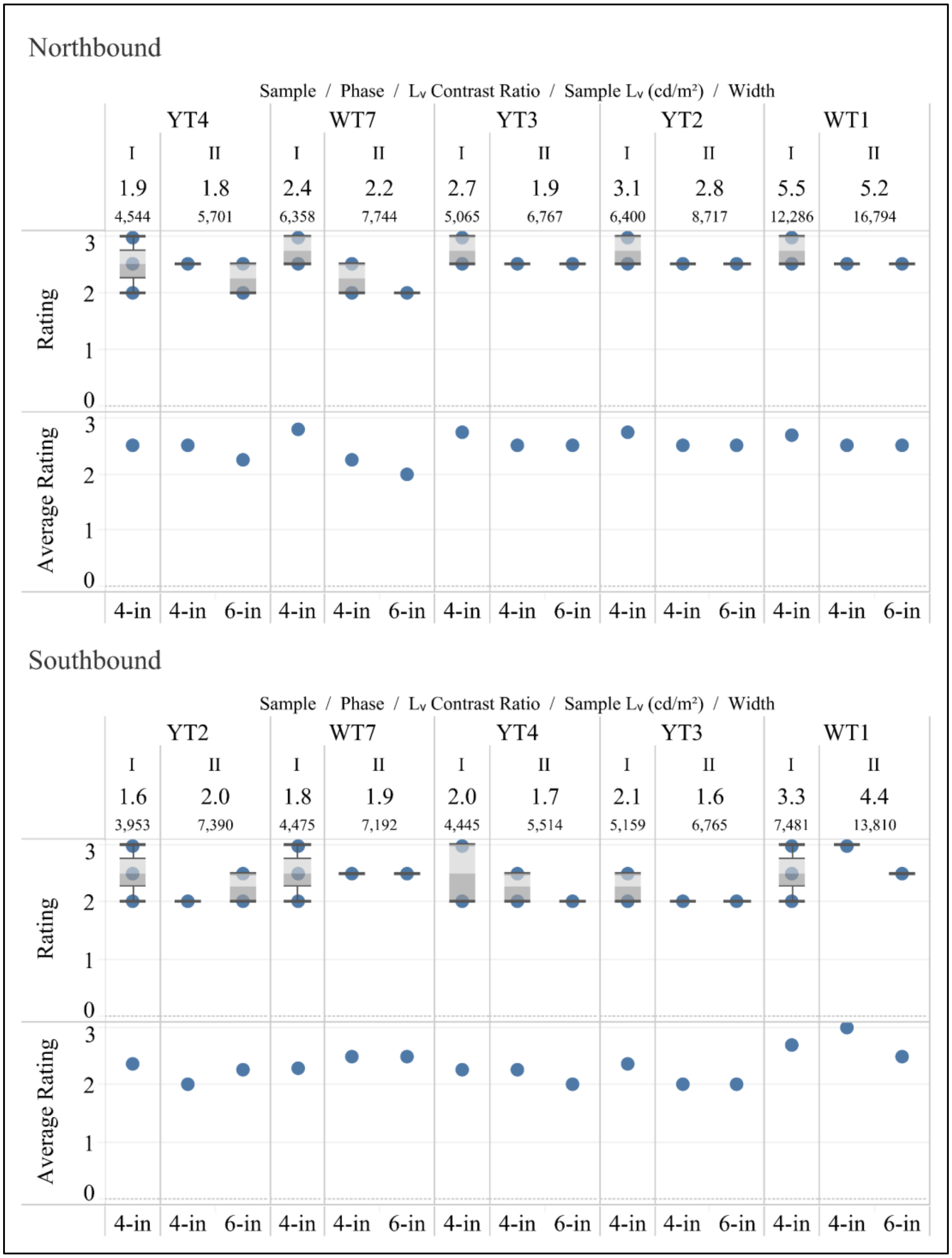


Sample WT1

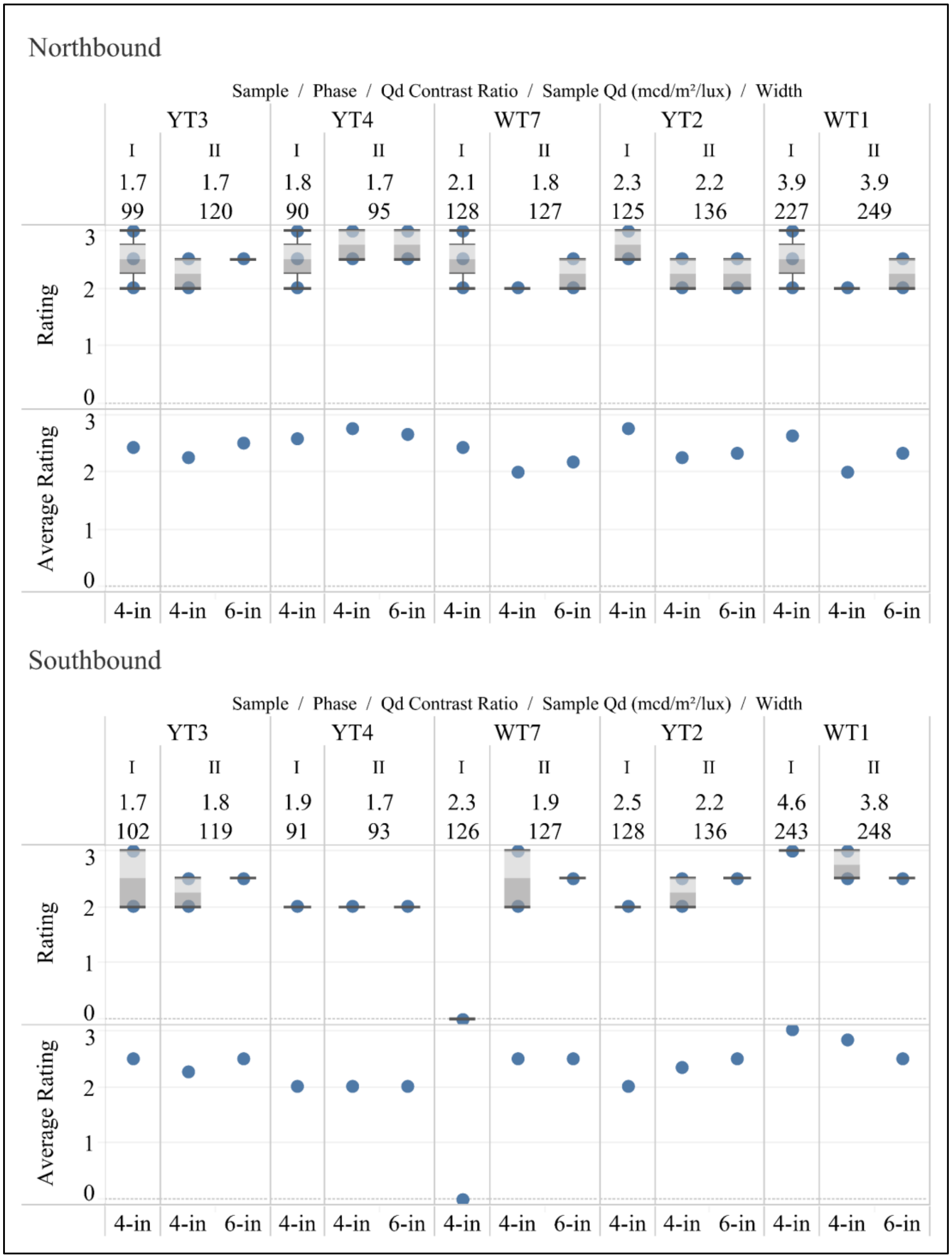
APPENDIX C: BOX-AND-WHISKER PLOTS OF RATING VERSUS Qd AND CCD MOBILEYE GEOMETRY LUMINANCE



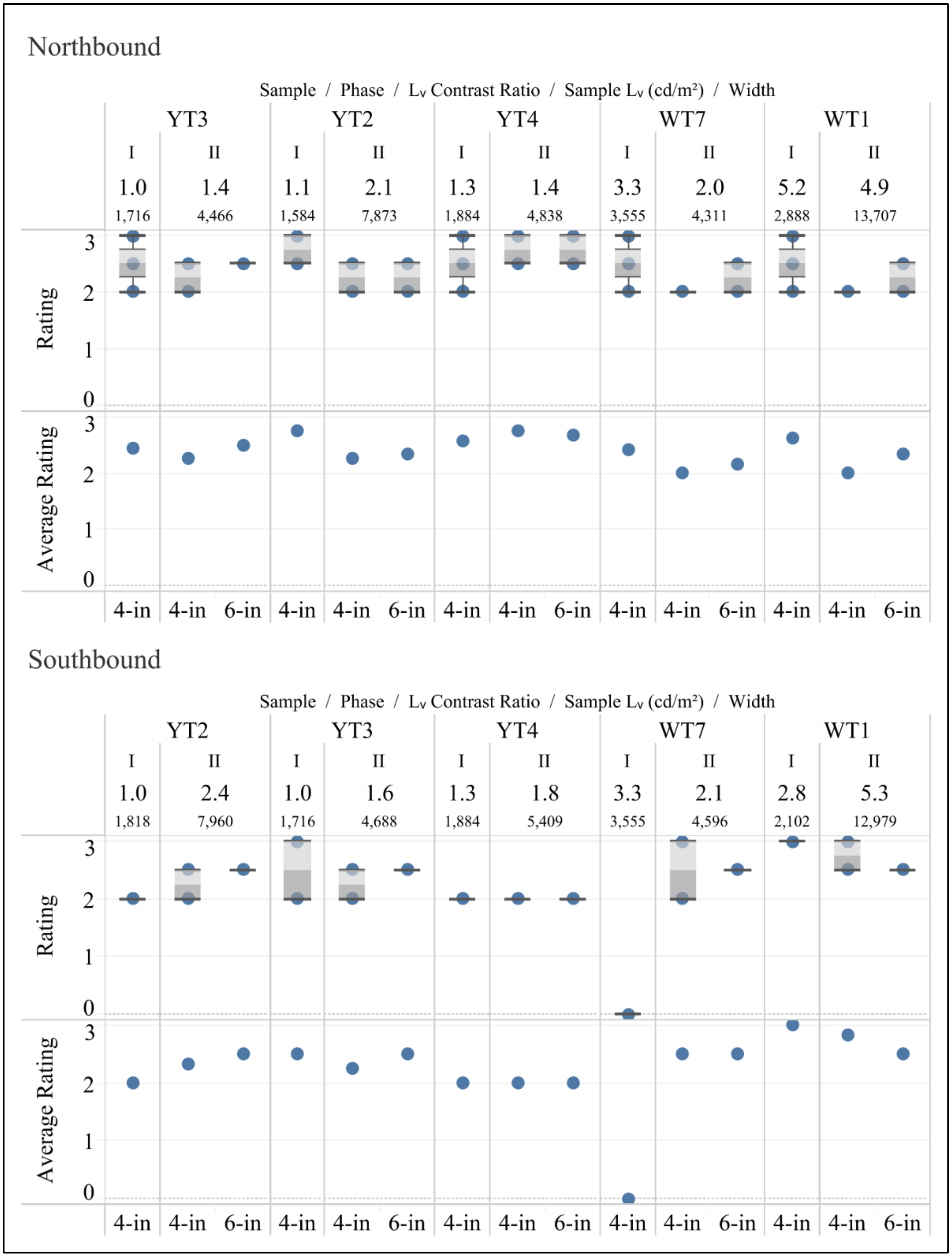
4- and 6-inch Phase II Sample vs. Qd Contrast Ratio, Dry, Daytime Conditions



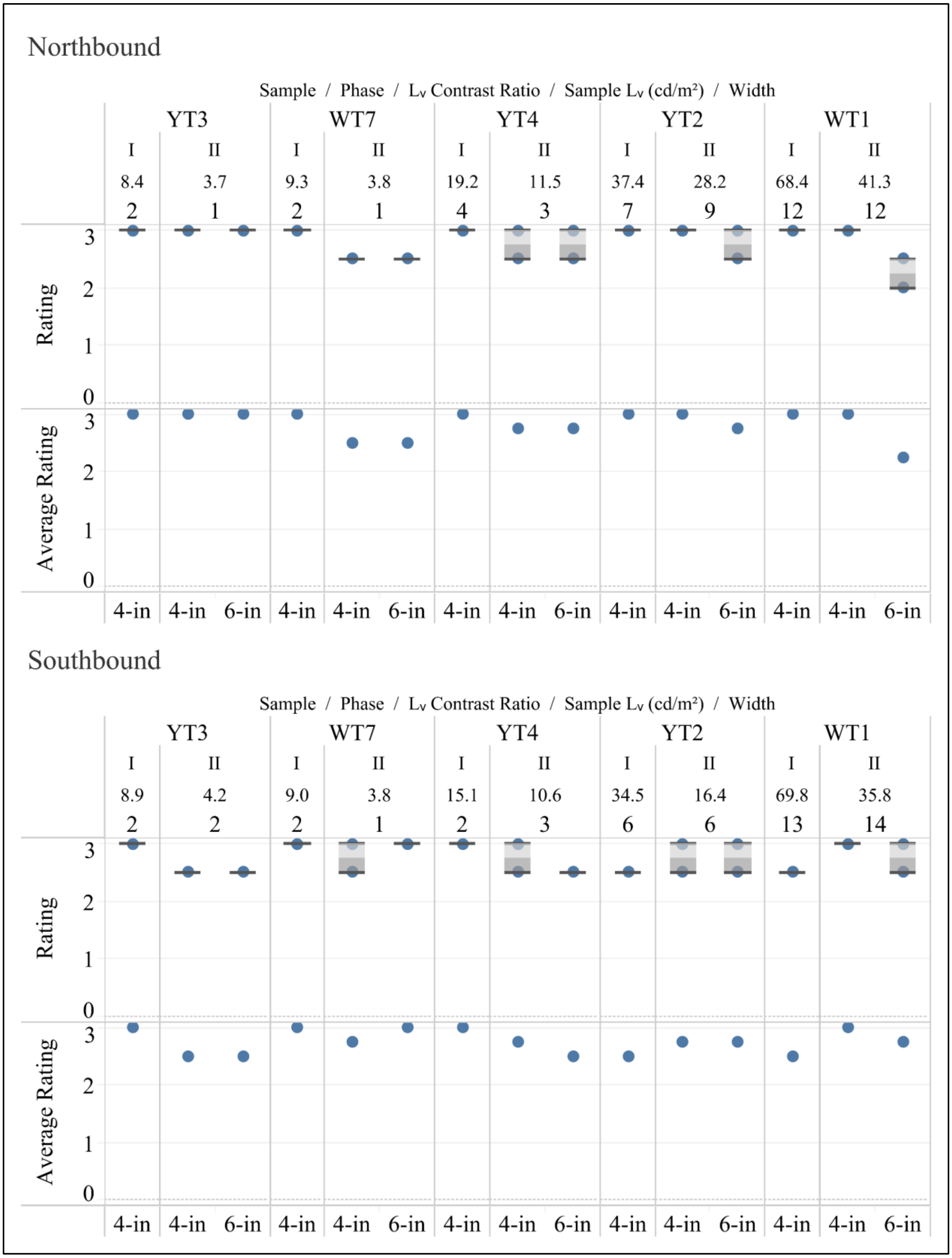
4- and 6-inch Phase II Sample vs. Luminance Contrast Ratio, Dry, Daytime Conditions



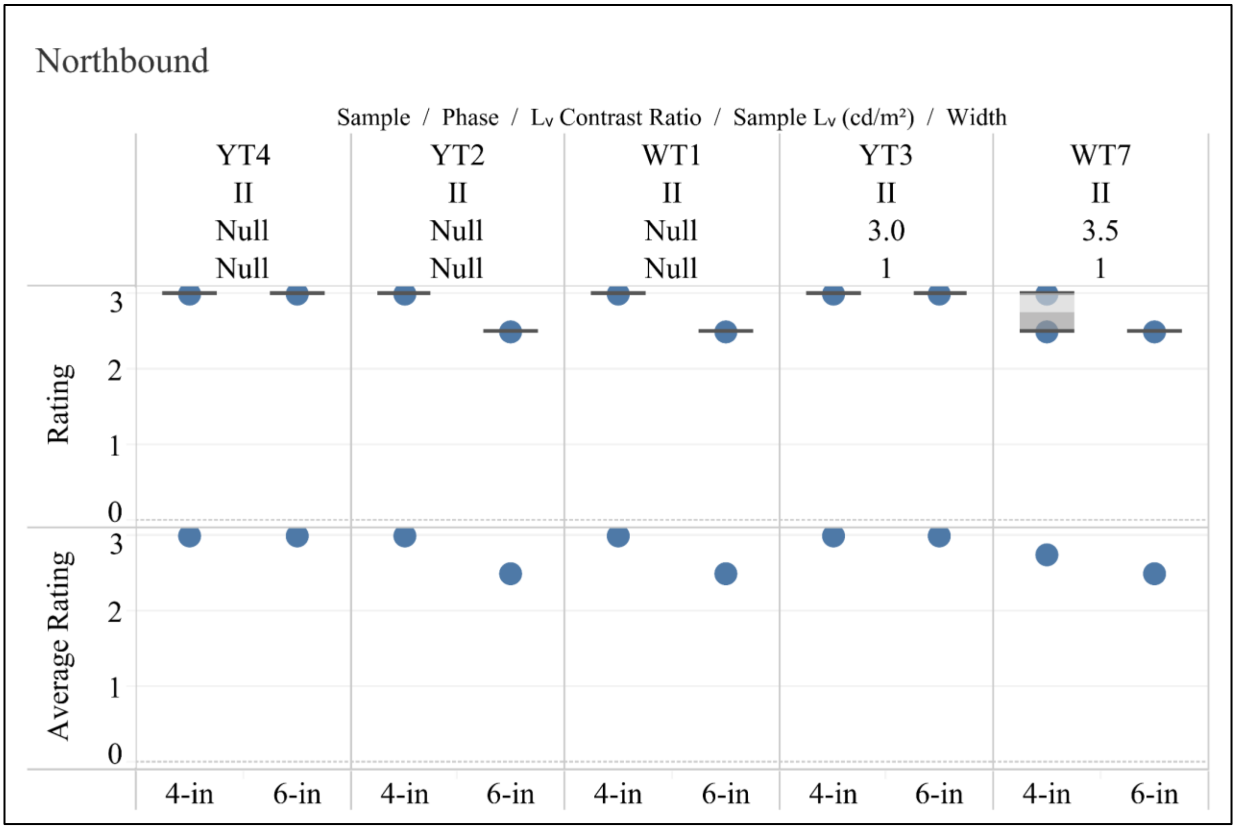
4- and 6-inch Phase II Sample vs. Qd Contrast Ratio, Wet, Daytime Conditions



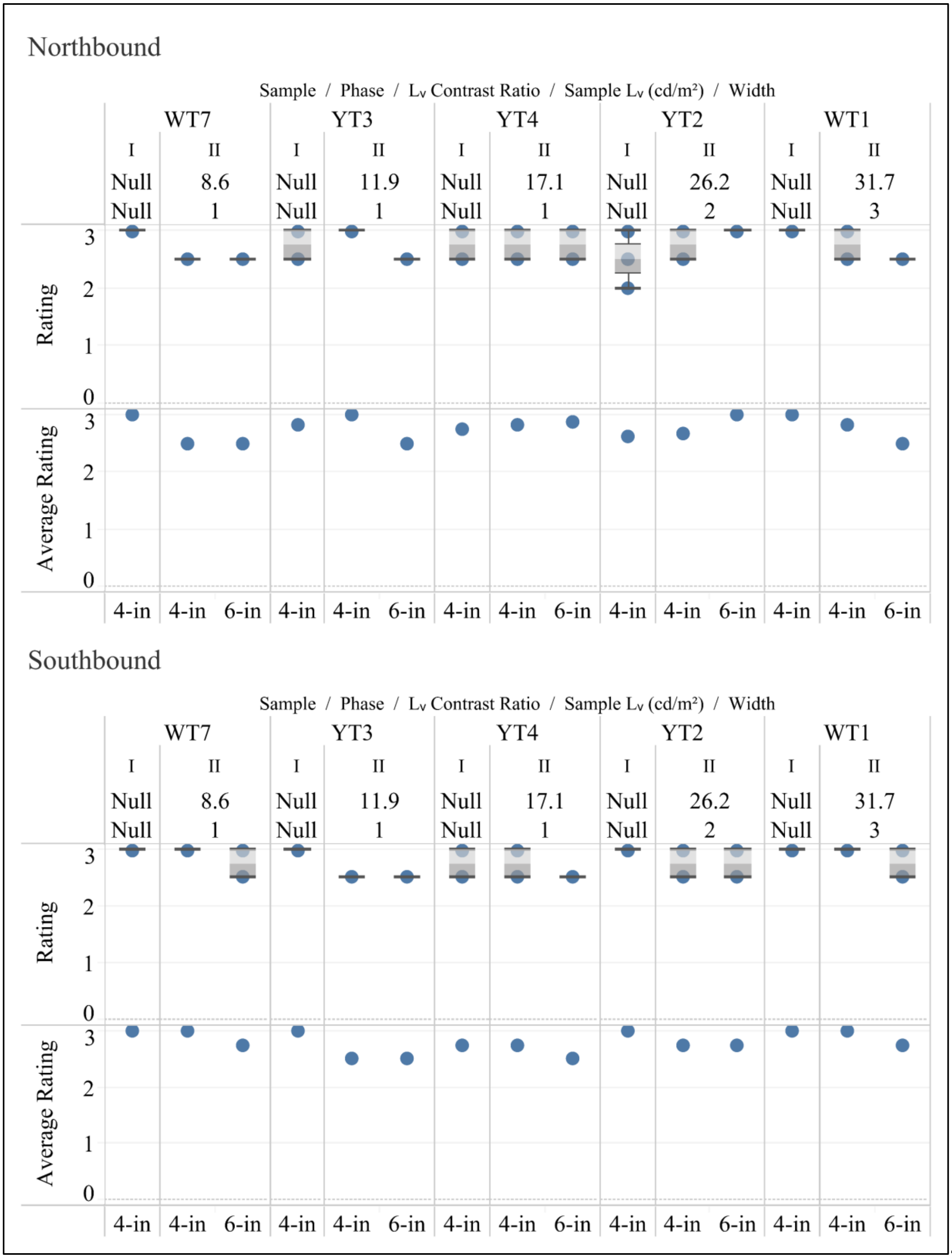
4- and 6-inch Phase II Sample vs. Luminance Contrast Ratio, Wet, Daytime Conditions



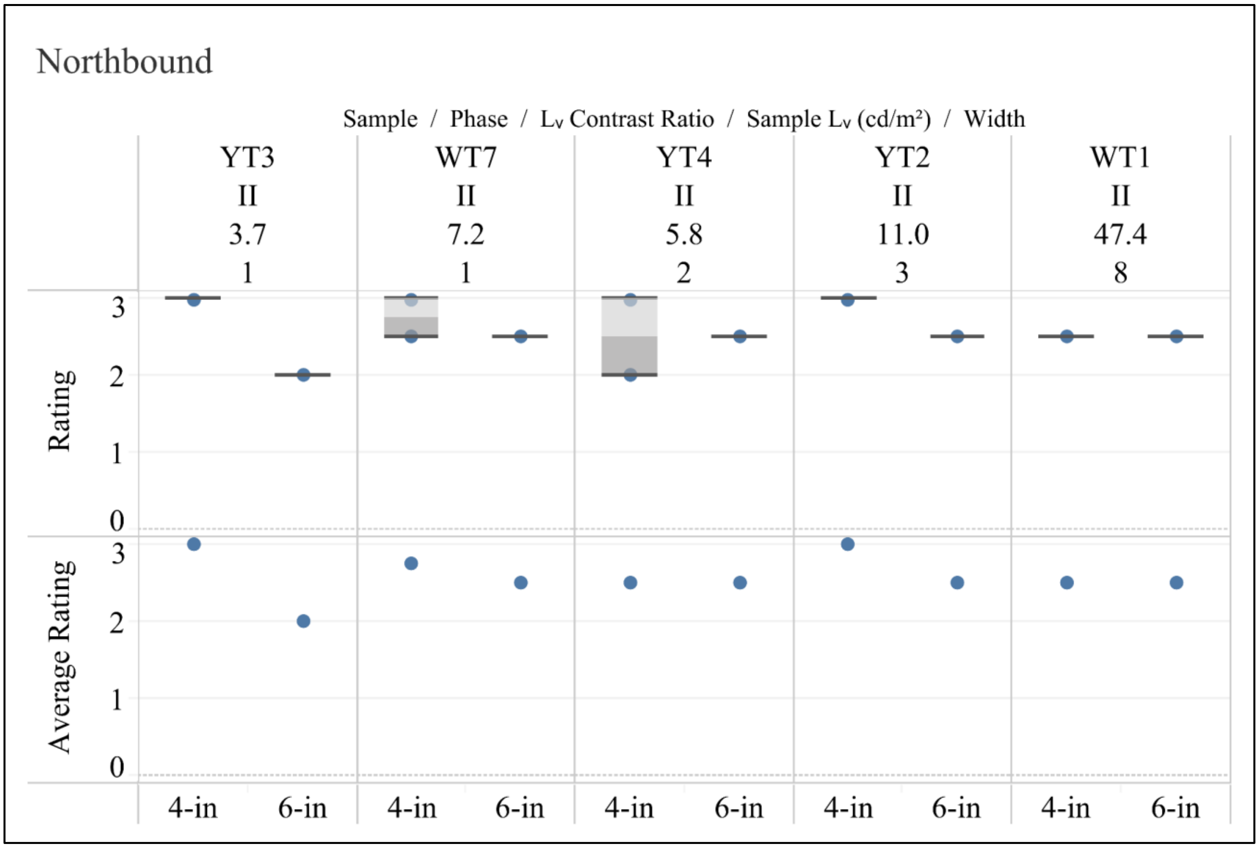
4- and 6-inch Phase II Sample vs. Luminance Contrast Ratio, Dry, Nighttime Conditions



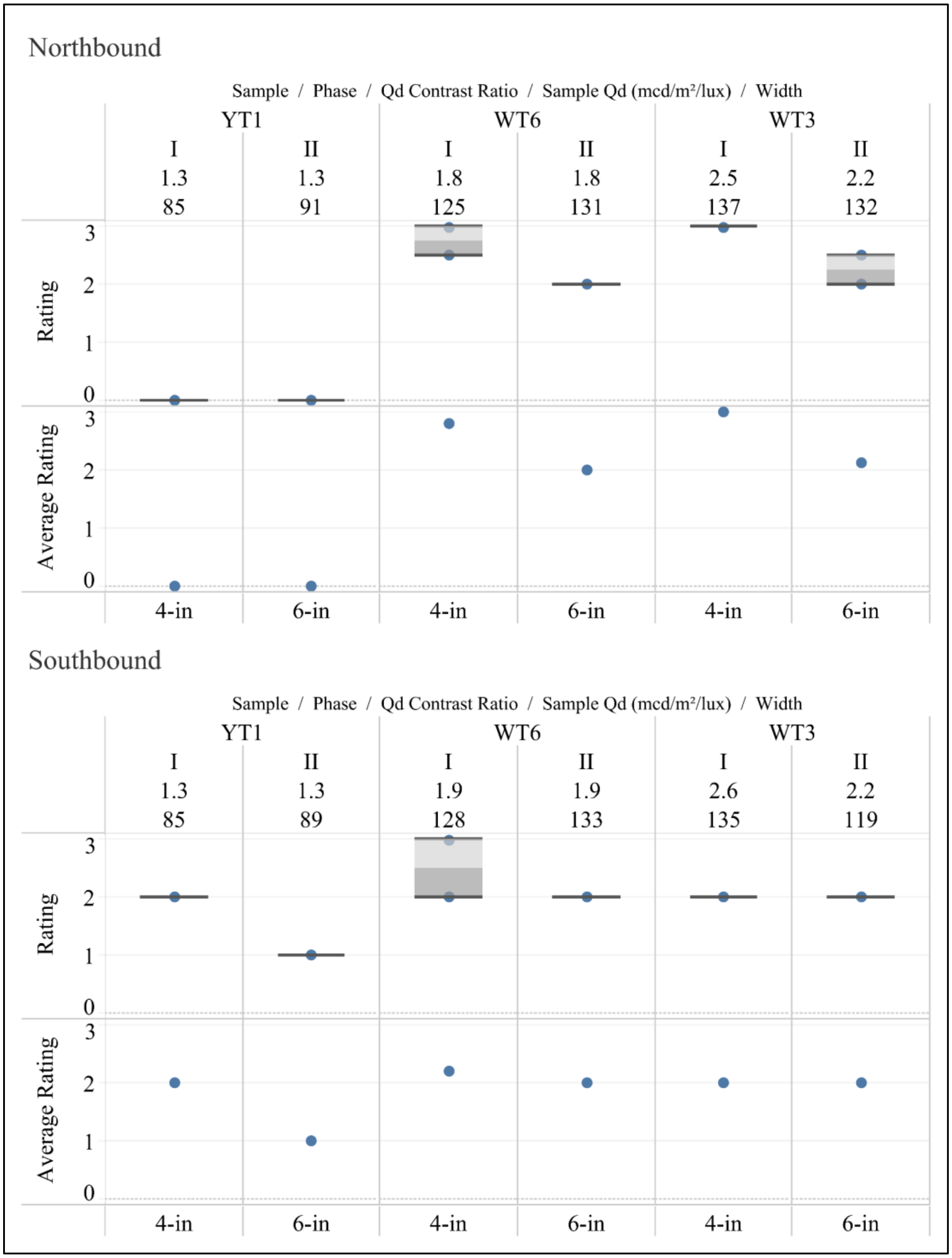
4- and 6-inch Phase II Sample vs. Luminance Contrast Ratio, Dry, Nighttime, Glare Conditions



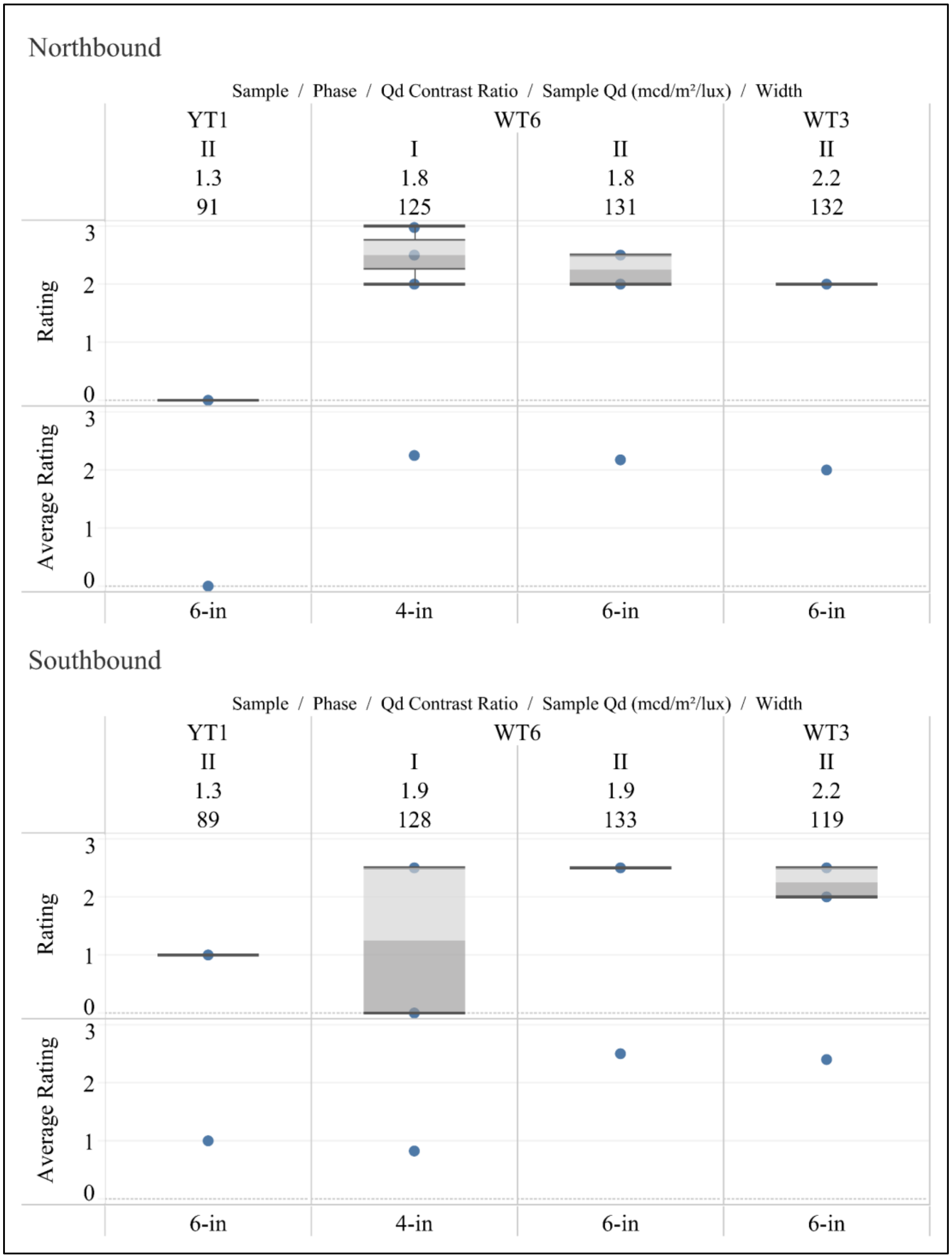
4- and 6-inch Phase II Sample vs. Luminance Contrast Ratio, Wet, Nighttime Conditions



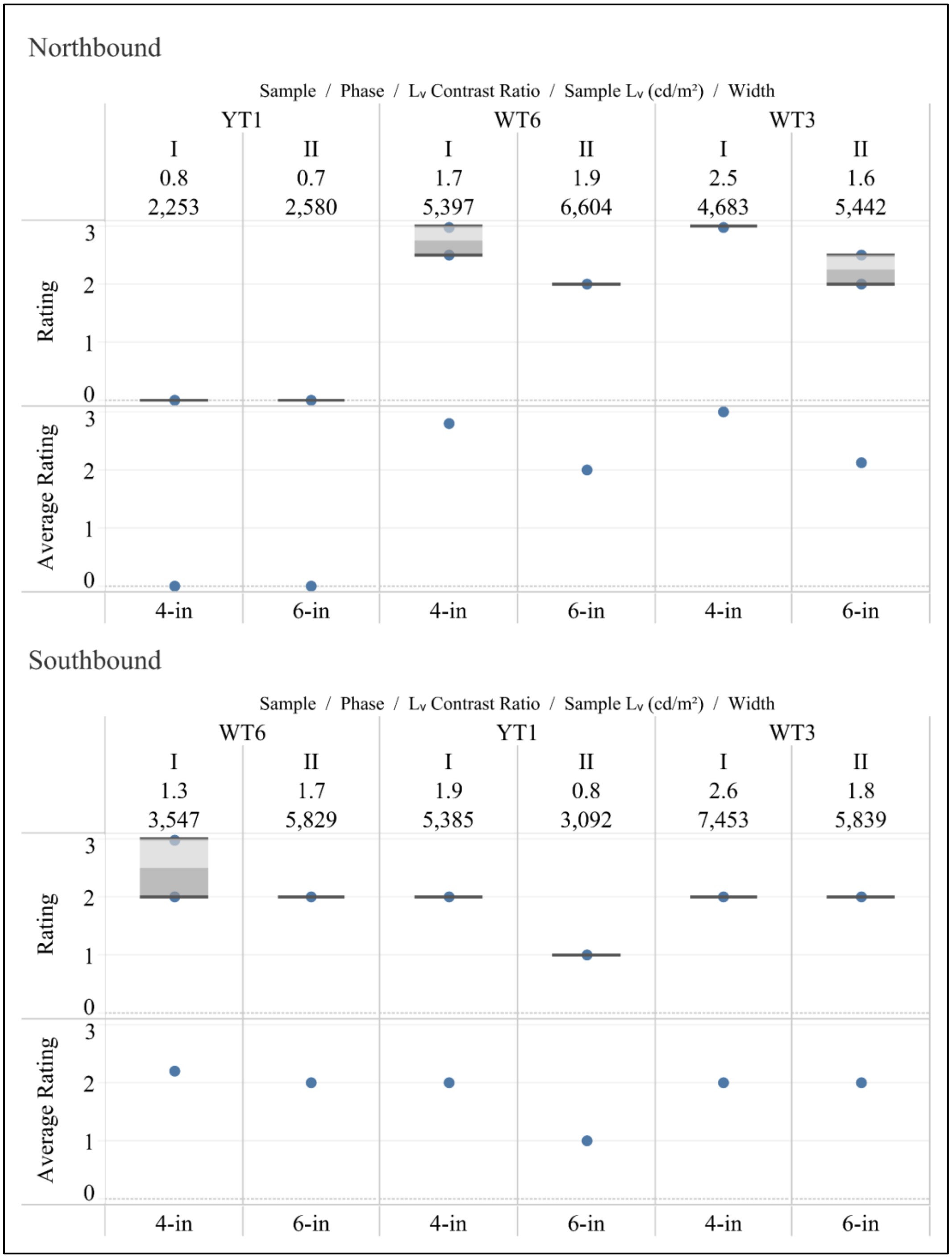
4- and 6-inch Phase II Sample vs. Luminance Contrast Ratio, Wet, Nighttime, Glare Conditions



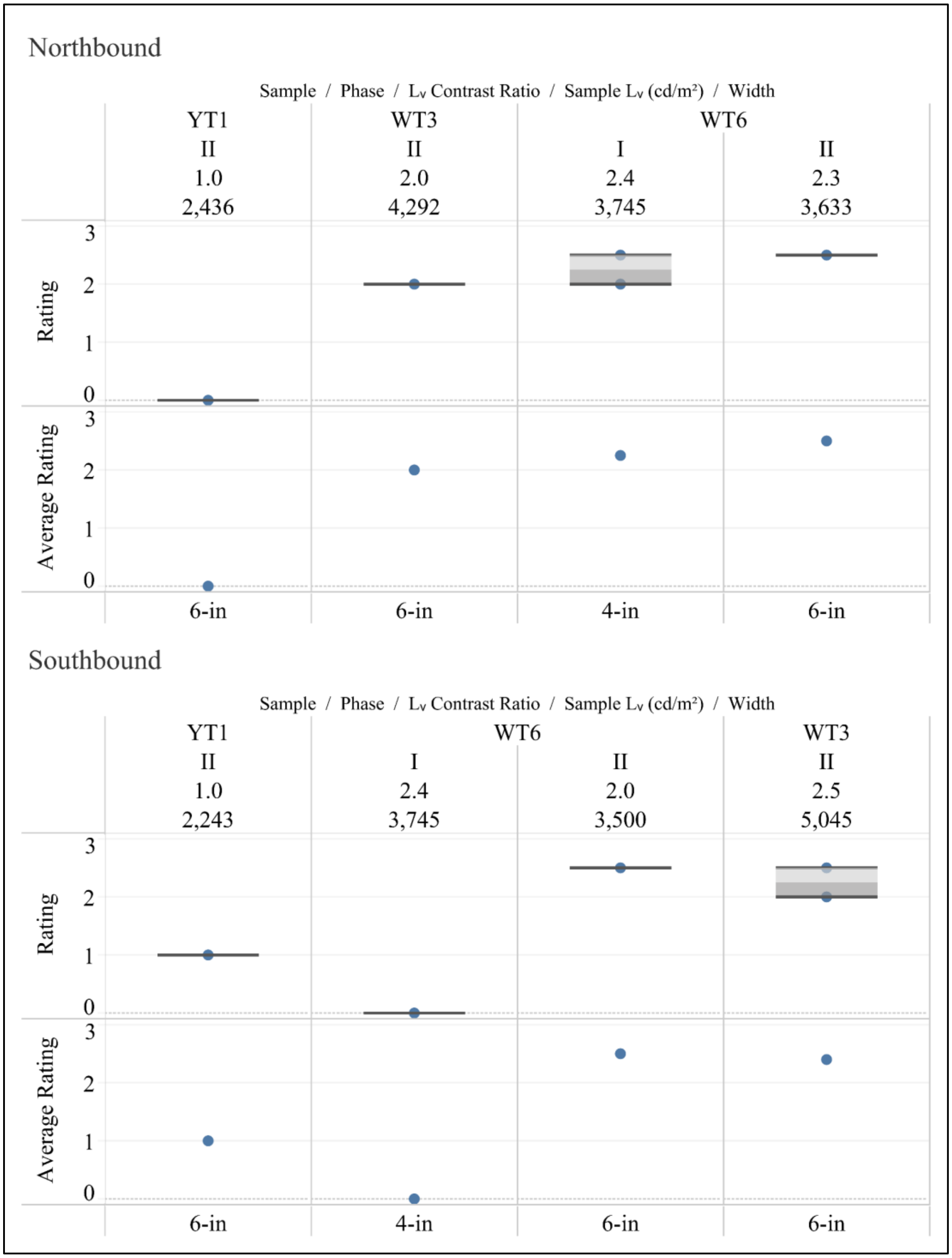
6-inch Phase II Sample vs. Qd Contrast Ratio, Dry, Daytime Conditions



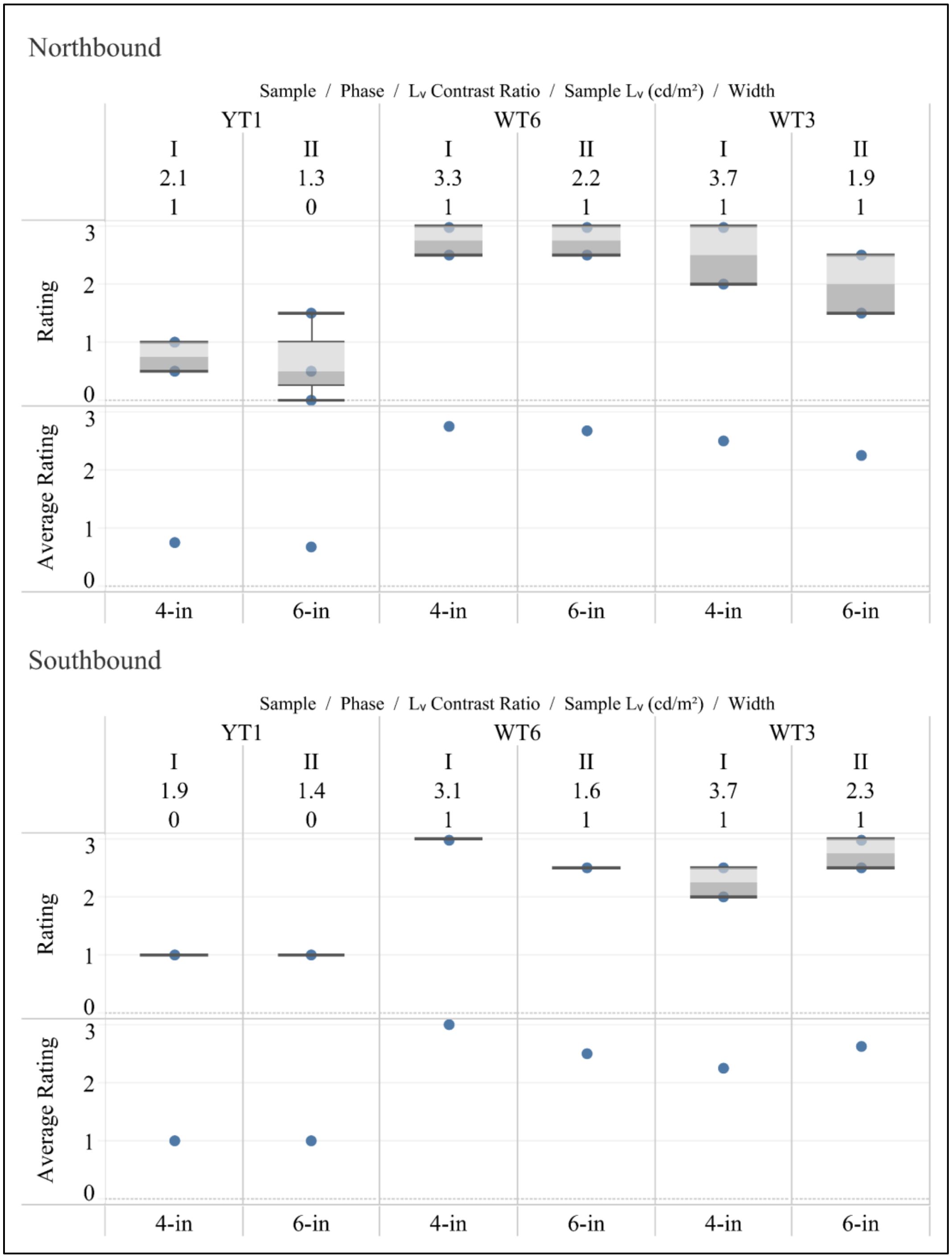
6-inch Phase II Sample vs. Qd Contrast Ratio, Wet, Daytime Conditions



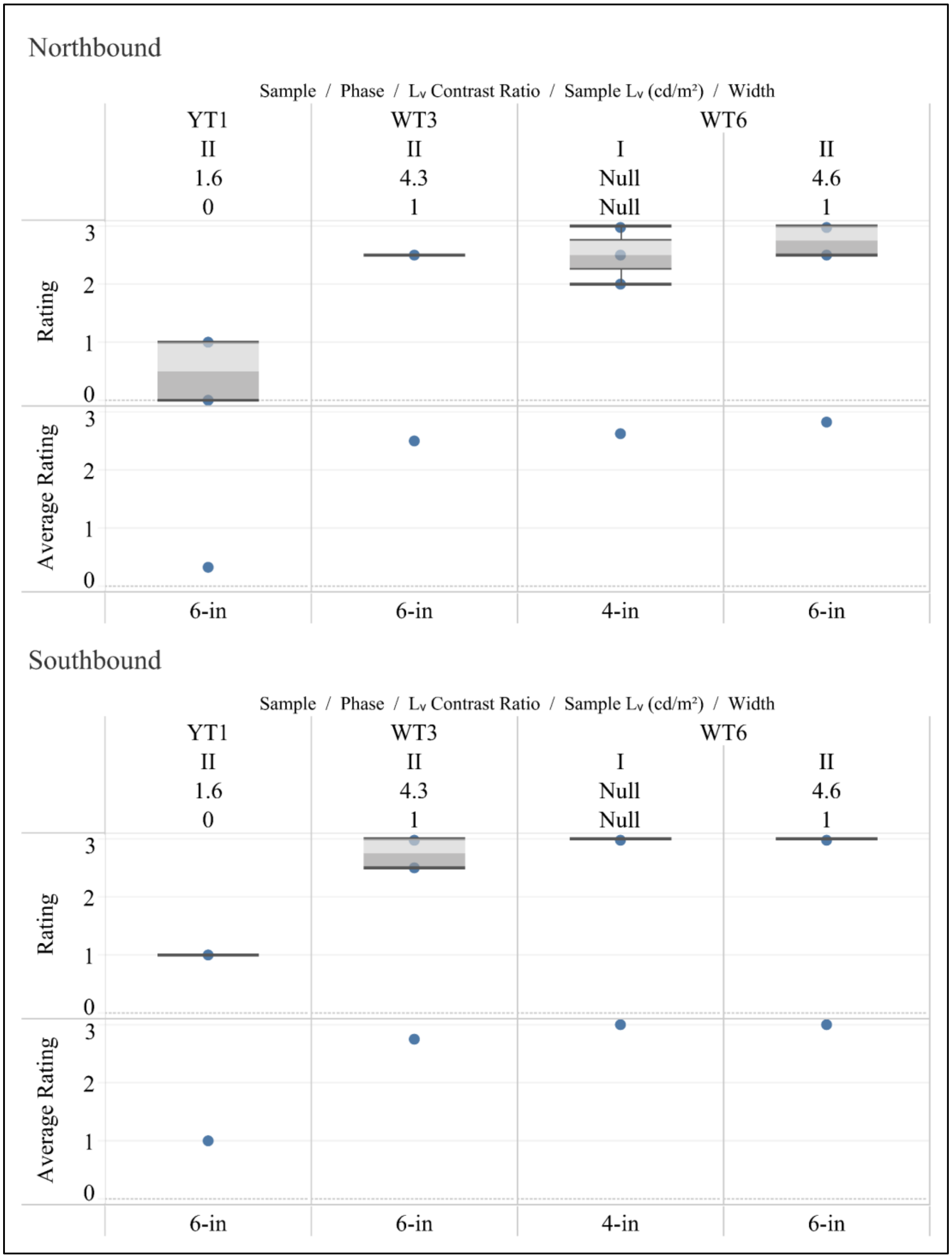
6-inch Phase II Sample vs. Luminance Contrast Ratio, Dry, Daytime Conditions



6-inch Phase II Sample vs. Luminance Contrast Ratio, Wet, Daytime Conditions



6-inch Phase II Sample vs. Luminance Contrast Ratio, Dry, Nighttime Conditions



6-inch Phase II Sample vs. Luminance Contrast Ratio, Wet, Nighttime Conditions

American Traffic Safety Services Association
15 Riverside Parkway, Suite 100
Fredericksburg, VA 22406
800-272-8772 • www.atssa.com