Traffic Control Devices: Considerations to Support Automated Vehicle Deployment

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1. Introduction

The evolution and deployment of automated vehicles (AVs) has continued to increase over the last few years with expectations of accelerated deployments within the coming decades. In order to realize the safety and efficiency potential of AVs, transportation agencies are trying to understand what elements of the roadway infrastructure are important for AV operation and therefore may be designed, specified, operated, and/or maintained differently than today. One of the early signs related to AV impacts is that the traffic control device (TCD) infrastructure appears to be an element within the larger roadway infrastructure space where near-term opportunities exist to support AV deployment. Transport Canada has identified an opportunity to study and understand the needs of AVs related to TCDs.

For many years now, the AV developing community have been mentioning in qualitative terms how TCDs can support AV deployment. For instance, in 2013 Michael J. Robinson of General Motors testified before the House Committee on Transportation and Infrastructure Subcommittee on Highway and Transit saying that, “one of the key highway needs is to provide – at a minimum – clearly marked lanes and shoulders.” In 2015, Elon Musk tweeted about the low contrast markings in California. In 2016, Volvo’s North American CEO, Lex Kerssemakers, became frustrated as the automaker’s semi-autonomous prototype sporadically refused to drive itself during a press event at the Los Angeles Auto Show. “It can’t find the lane markings!” Kerssemakers complained to Mayor Eric Garcetti, who was behind the wheel. “You need to paint the bloody roads here!”

Even today, the ask of the infrastructure industry is mostly general and qualitative. The National Committee on Uniform Traffic Control Devices (NCUTCD)[1] has been the source of much of the detailed information related to TCDs. Within the NCUTCD, a CAV Task Force was established in 2017 that engaged externally with AV stakeholders specifically in search of relevant TCD information that can support AV deployment while also being beneficial to human-led vehicles. This topic area is relatively young and therefore there is not many traditional research references. The material in this report represents the current state of knowledge, which is bound to continue to expand as the paths toward AV become clearer.

1.1. Objective

The objective of this study is to identify, review, and synthesize available research, as well as on-going research, that includes information related to how TCD enhancements can support AV deployment.

[1] The National Committee on Uniform Traffic Control Devices (NCUTCD) is an organization whose purpose is to assist in the development of standards, guides and warrants for traffic control devices and practices used to regulate, warn, and guide traffic on streets and highways. The NCUTCD recommends to the Federal Highway Administration (FHWA) proposed revisions and interpretations to the Manual on Uniform Traffic Control Devices (MUTCD). https://ncutcd.org/

For this report, the term AV is meant to provide a broad description of any vehicle equipped with driving automation technologies as defined in SAE J3016 (see Figure 1). There are two primary categories of AV:

1. Advanced Driver Assistance Systems (ADAS), which include lower levels of automation (SAE J 3016 Levels 1 and 2), and
2. Automated Driving Systems (ADS), which cover the higher levels of automation (SAE J 3016 Levels 3 - 5) (*1*).

For reference, only ADAS-equipped vehicles are available for private ownership (as of March 2021). Vehicles within the ADS category are operating in certain geo-fenced areas, but usually they are low-speed people movers or robo-taxis operating in "testing" or "experimental" phases of deployment. A short description of AV growth is provided in the next section of the report.

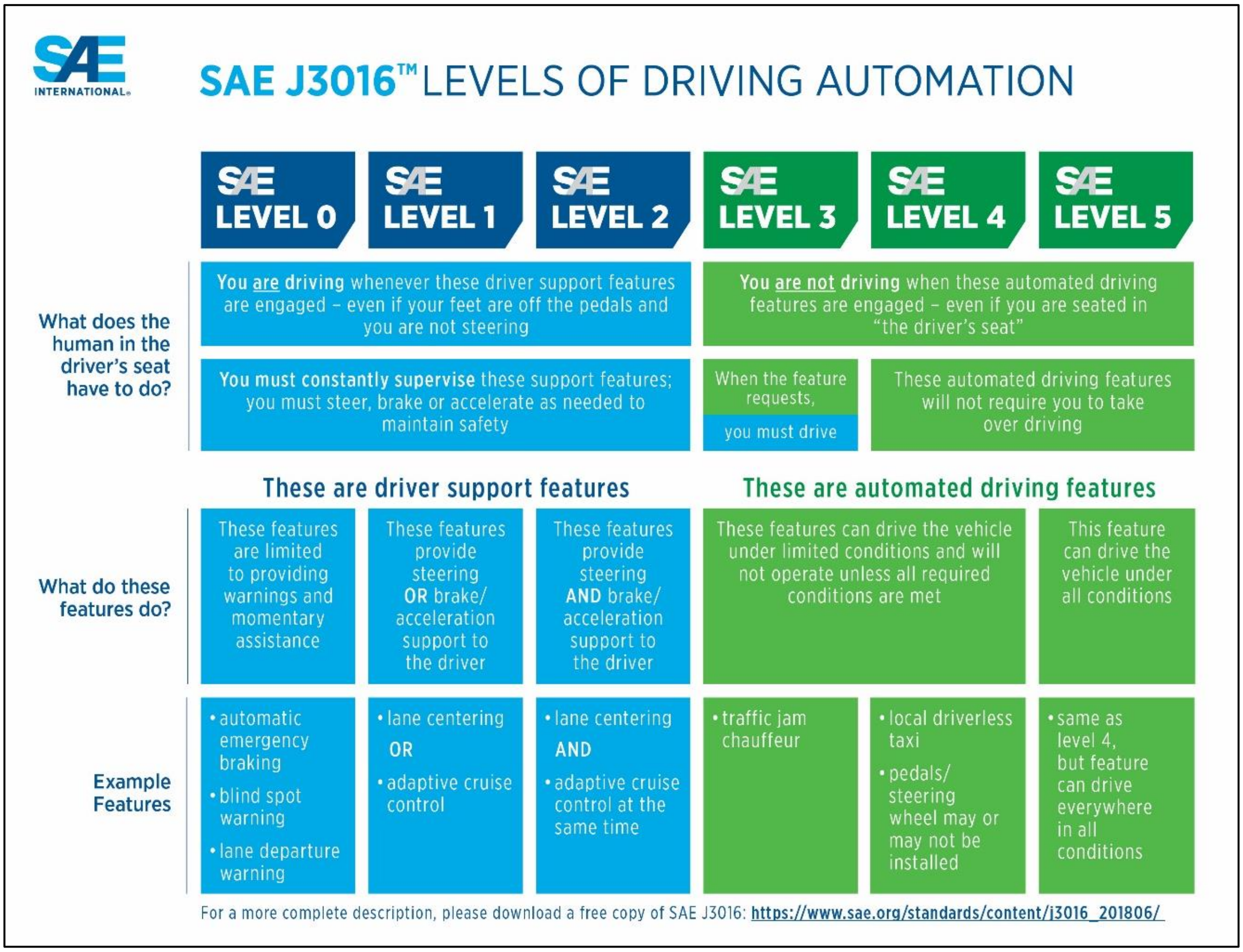

Figure 1. Levels of Driving Automation (SAE J3016)

1.2. Project Scope

The goal of this project is to provide the latest TCD infrastructure information to support AV deployment as agencies plan and prepare for a transportation evolution fueled by AVs. There are many ways to describe the evolution of AVs. One way is shown in Figure 2 where there are two primary paths terminating with Level 4 to 5 automation (where the driver is relieved of the driving task at least part of the time). In the "evolutionary" path, traditional automotive manufacturers and their suppliers continue to develop and sell vehicles that advance automation in small increments with an eventual goal of reaching ADS. Today, these vehicles are ADAS-equipped and the ADAS technology and performance continues to be refined. Currently, this "evolutionary" path is mostly designed to be deployed on freeway type facilities. On the other hand, the "revolutionary" path toward ADS includes technology-focused companies that are not traditionally known as automotive OEMs. These companies are building small fleets of vehicles that operate in a testing or experimental phase in geo-fenced commercialized areas that have been heavily mapped. The vehicles mostly operate with a safety driver and they are not available for private purchase.

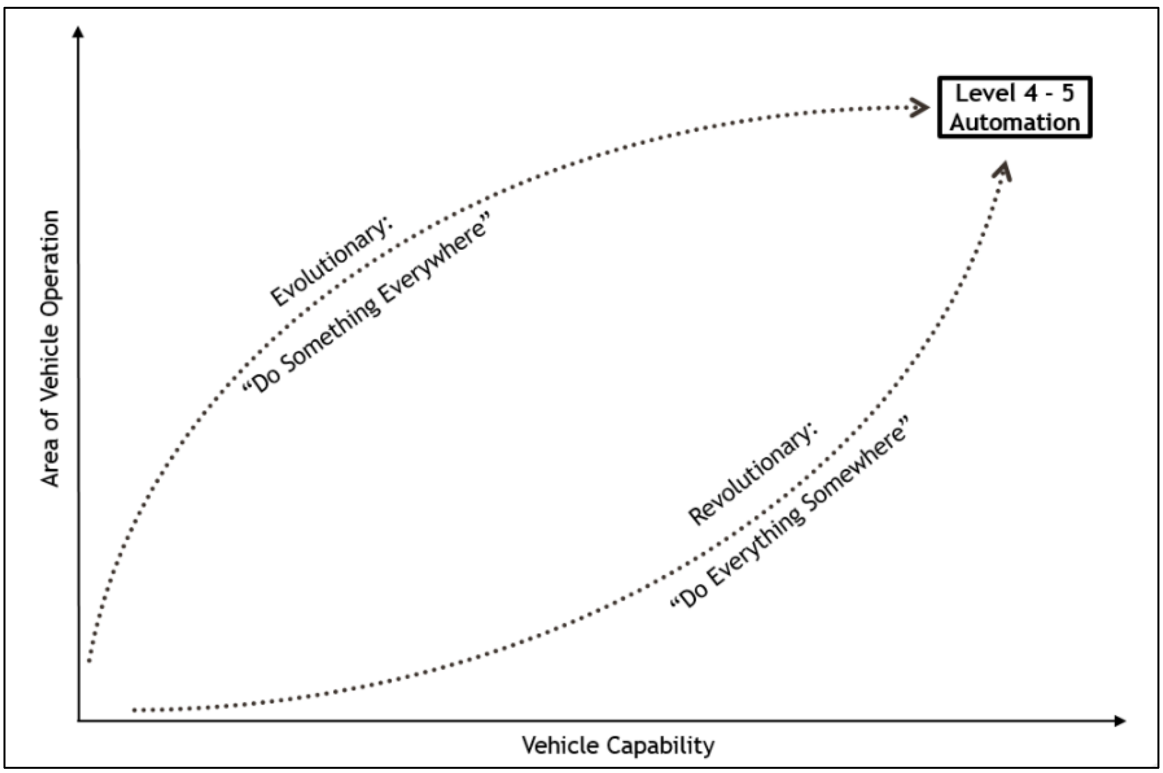

Figure 2. Paths of Vehicle Automation

While there are many nuances that add complexity to the evolution of AVs, the paths shown in Figure 2 help frame the scope of this report. As of early 2021, most of the relevant information available pertains to the ADAS category of AVs and therefore this report covers enhancements to the TCD infrastructure to support ADAS deployment (the "evolutionary" path shown in Figure 2).

The content of this report is based on currently available information, which has been harvested from research and other sources derived from an automation path that is evolving from basic ADAS capabilities to refined ADAS capabilities with an eventual, but not yet achieved goal, of ADS where the driver may be relieved of driving duties under certain conditions. Figure 3 shows data demonstrating that this slow evolution of ADAS capabilities (SAE J3016 Levels 1 and 2) will continue for at least another 10 years.

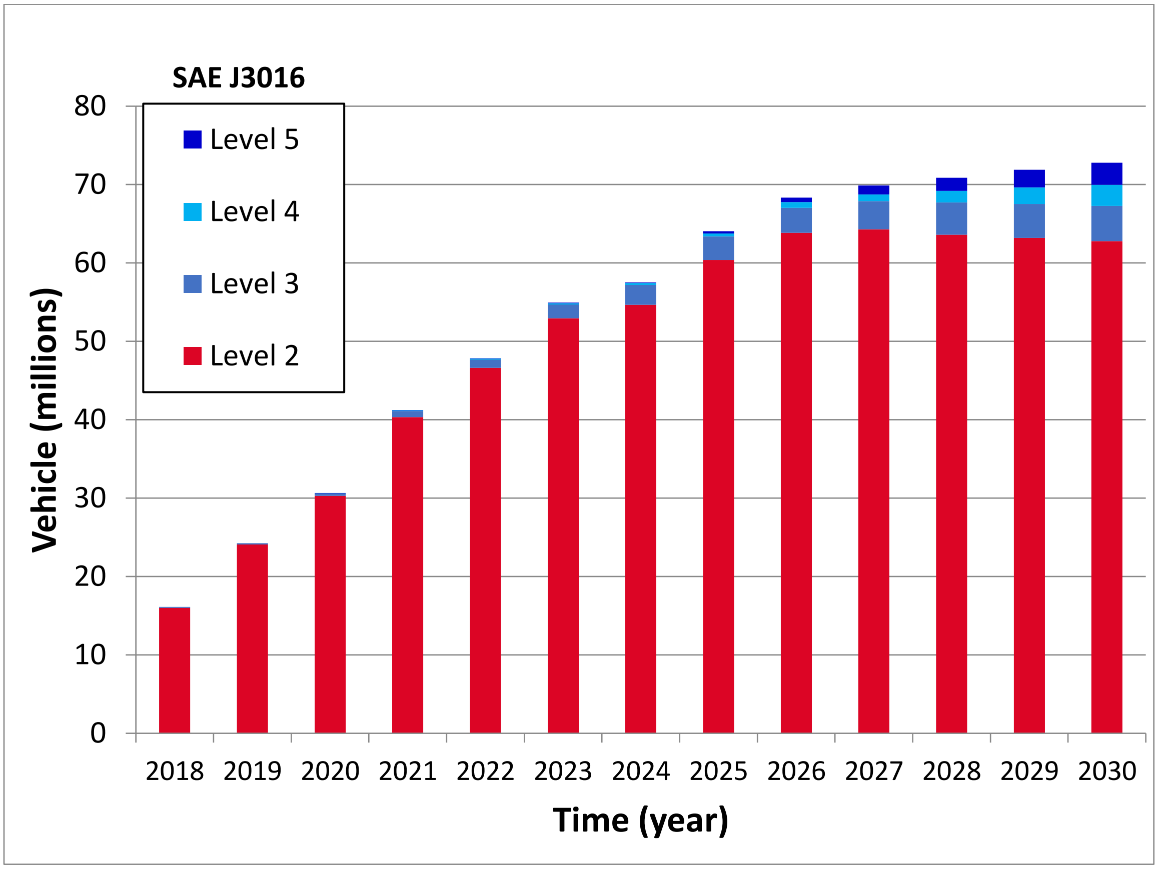

Figure 3. Anticipated Evolution of Vehicle Automation Levels (Source: Automotive Safety Council, 2020)

As shown in Figure 3, ADAS-equipped vehicles will still be the dominant type of AV for the next decade. Therefore, the TCD infrastructure findings documented in this report are expected to be valid for at least another 10 years and most likely decades to follow given that there will be a mixed fleet of vehicles. This is also consistent with a recent finding from an FHWA study where the AV developer industry confirmed that upgrades to support ADAS-equipped vehicles will remain useful once ADS become available (*5*).

Despite the growth in vehicle automation as shown in Figure 3, there will be many decades of a mixed fleet operating on the road system. Therefore, it is important to note that the findings from this report should be married with traditional long-standing TCD design, operation, and maintenance practices since road users will constitute an evolving mix of human-led vehicles and AVs.

Connected vehicles are another related but different mobility trend that is often associated with automated vehicles (major mobility trends: automated vehicles, connected vehicles, shared-use vehicles, electric vehicles). Connected vehicles are equipped with a wireless communication device to communicate with other cars on the road, roadside infrastructure, and/or the cloud. This report is focused on the physical aspects of the TCD infrastructure and does not include connected vehicle topics such as digital infrastructure, roadside communication devices, or other aspects of connected vehicle operation.

Finally, this report does not delve into operations or policy, although TCD infrastructure impacts outlined in this report may be contingent upon operations and policy decisions.

1.3. Report Structure

The remainder of this report is organized into six more chapters. Chapter two includes a synthesis of research and perspectives on four TCD categories: pavement markings, traffic signs, traffic signals, work zone TCDs, and then a summary of the findings, categorizing them into three areas: convergence, divergence, and incomplete. Chapter 3 presents the results of an on-going NCHRP study that surveyed US DOTs to determine how they have been preparing for AV deployment as it relates to changes to TCDs. Chapter 4 includes a description of agency concerns, as identified during a recently completed FHWA study. Chapter 5 includes a conceptual framework to prioritize TCD considerations that were identified as supporting AV deployment. Chapter 6 includes a set of recommended research problem statements based on the limitations of the current state of knowledge as identified during the work to development this report. Finally, Chapter 7 includes a list of references used to develop this report.

2. Literature Review

This chapter describes specific TCD research findings and suggestions that have been made to support AV deployment. While specific TCD provisions are listed and described in this chapter, the highest level of need, and the most common request among AV developers, is uniform application and maintenance of TCDs (*2-3*). This need was clearly identified in 2018 when the Federal Highway Administration (FHWA) published 10 questions in the *Federal Register* (January 18, 2018) as a Request for Information (RFI) (*4*). The questions were specifically designed to help FHWA better understand the needs of transportation infrastructure to support AV deployment. In May 2018, the FHWA summarized the top findings from the RFI as follows:

- **Greater uniformity and quality in road markings and traffic control devices** would enable automation. **Having greater consistency in road markings and traffic control devices** and an improved state of good repair benefits all road users, including AVs.
- All commenters suggested that the FHWA take a leadership role in convening stakeholders to encourage collaboration. Commenters expressed a desire for the FHWA to play a stronger

leadership role in convening state and local transportation agencies, automotive/AV developers, and other groups to discuss infrastructure needs and encourage collaboration.

- Certain data elements around the roadway environment are useful for industry and state and local DOTs to share and could improve automation operations. Commenters identified specific data elements that could be shared such as work zone data, traffic laws, traffic incident data, weather conditions, and speed limits.
- Conducting pilots and supporting pilot testing are important for facilitating learning, collaboration, and information sharing. Commenters expressed the importance of supporting pilot deployments and testing in order to actively engage with industry, assess AV benefits and learn about the real-world interactions that AV could have with the roadway infrastructure.
- Uncertainty in infrastructure investment and allocation of limited resources is a key concern for state and local agencies. Because the infrastructure requirements and timing of AV technology remain unclear, many state and local DOTs are unlikely to invest significantly in infrastructure improvements for automation.

As automated vehicle technology was being introduced to the vehicle fleet, the infrastructure needs were not well understood and were mostly qualitative in nature such as "needing greater uniformity and quality in road markings." More recently, a more quantitative understanding has been developing. The remainder of this report is meant to summarize the areas where a quantitative understanding has been or is developing.

2.1. Pavement Markings

Longitudinal pavement markings have been described as the rails for AVs and are the most common type of TCD that is mentioned and researched in terms of any specific highway infrastructure element supporting AV deployment. ADAS-equipped vehicles detect and track longitudinal pavement markings to provide features such as lane departure warning, lane keep assist, and lane centering assist. Passive forward looking cameras mounted behind the windshield are used along with complex software to locate markings, track markings, and even provide predictive scripts when markings are occluded by nearby vehicles. Furthermore, ADS developers have reported that their sensor suites will also use pavement markings for the same reasons as ADAS-equipped vehicles but also for redundancy and to ensure that the vehicle is located where the software thinks the vehicle is located (*5*).

One of the remaining challenges to deploy AVs is winter conditions in places like Canada. Snow covered roadways provide a barrier where the vehicle sensors cannot detect the road markings. In addition, winter maintenance activities such as snow plowing, and the use of studded tires, tend to severely degrade pavement markings to the point that their presence is nearly obliterated come springtime. While these conditions provide a serious challenge for today's ADAS-equipped vehicles, one possible solution for future ADS vehicles comes from Finland where the idea of using roadside reflector posts (and snow poles) may assist ADS vehicles with precise vehicle positioning to overcome the existing challenges described above (see: https://julkaisut.vayla.fi/pdf8/lts_2016-19eng_road_transport_web.pdf).

Another specific issue for areas such as Canada is decreased pavement marking contrast when salt residue remains on the roadway. The effects of salt residue can camouflage pavement markings. Research from Norway shows that during these conditions, yellow markings can be easier to detect than white markings (*25*).

2.1.1. Longitudinal Pavement Marking Width

Studies have evaluated the detectability of 4-inch wide pavement markings compared to 6-inch wide pavement markings (*6-9*). Consistently, the research findings suggest that 6-inch wide pavement markings provide more robust machine vision detection, particularly when visibility conditions are not ideal (e.g., worn markings, wet conditions, low contrast, glare, and skip lines at high speeds). The forward-looking cameras in ADAS-equipped vehicles are industrial quality and built to have a long life in all conditions (from extreme cold to extreme heat). A key tradeoff is that the vehicle forward-looking cameras have low resolution compared to consumer-level cameras found in conventional cell phones. It is important to keep in mind that forward-looking cameras (and their software) perform differently than human eyes. Testing in Texas showed that in ideal conditions (i.e., new markings with high contrast compared to the pavement), forward-looking cameras did not detect 6-inch markings any better than 4-inch markings while it is possible a human eye would have. However, in challenging visibility conditions, forward-looking cameras do detect 6-inch markings better than 4-inch markings (*7*).

The proposed US MUTCD[2], released in December of 2020, includes new provisions to standardize the width of pavement markings throughout the US. Previously, the MUTCD allowed for pavement marking widths between 4 and 6 inches and therefore the state-state practices have not been uniform. Some states have adopted 6-inch wide markings statewide while other states use 4-inch markings statewide. Most states have adopted a hybrid approach where they use 6-inch markings on high speed roadways and 4-inch elsewhere (see Figure 3). Some states split the difference and use 5-inch wide markings. Over the past ten years, there has been a trend across the US to adopt 6-inch wide markings, both to support AV deployment but also to provide added safety for human-led vehicles (*10*).

Specifically, the provisions in the proposed MUTCD include the following statements meant to tighten national uniformity (*11*):

Section 3A.04 Functions, Widths, and Patterns of Longitudinal Pavement Markings

The widths and patterns of longitudinal lines shall be as follows:

[2] The Manual on Uniform Traffic Control Devices (for Streets and Highways) is a FHWA document developed to ensure uniformity of traffic control devices across the USA. The use of uniform TCDs (messages, locations, sizes, shapes, and colors) helps reduce crashes and congestion, and improves the efficiency of the surface transportation system. Uniformity also helps reduce the cost of TCDs through standardization. The information contained in the MUTCD is the result of years of practical experience, research, and/or the MUTCD experimentation process. In December 2020, FHWA started rule-making to update the MUTCD, which is a major step toward developing the 11th Edition of the MUTCD. https://mutcd.fhwa.dot.gov/

Normal width line— 6 inches wide for freeways, expressways, and ramps; 6 inches for all other roadways with speed limits > 40 mph, 4 to 6 inches for all other roadways.

Wide line—at least 8 inches in width if 4 inch or 5 inch normal width lines are used and at least 10 inches in width if 6 inch normal width lines are used.

Section 3B.09 Edge Line Pavement Markings

Guidance: Regardless of the width of the normal line used on the roadway, edge lines on two-lane roadways should be at least 6 inches wide.

Similar to the proposed US MUTCD, a recent report from Australia also recommends 6-inch wide edge lines (*9*). This report also emphasized the need to harmonize road marking standards, a common request from the AV industry as well.

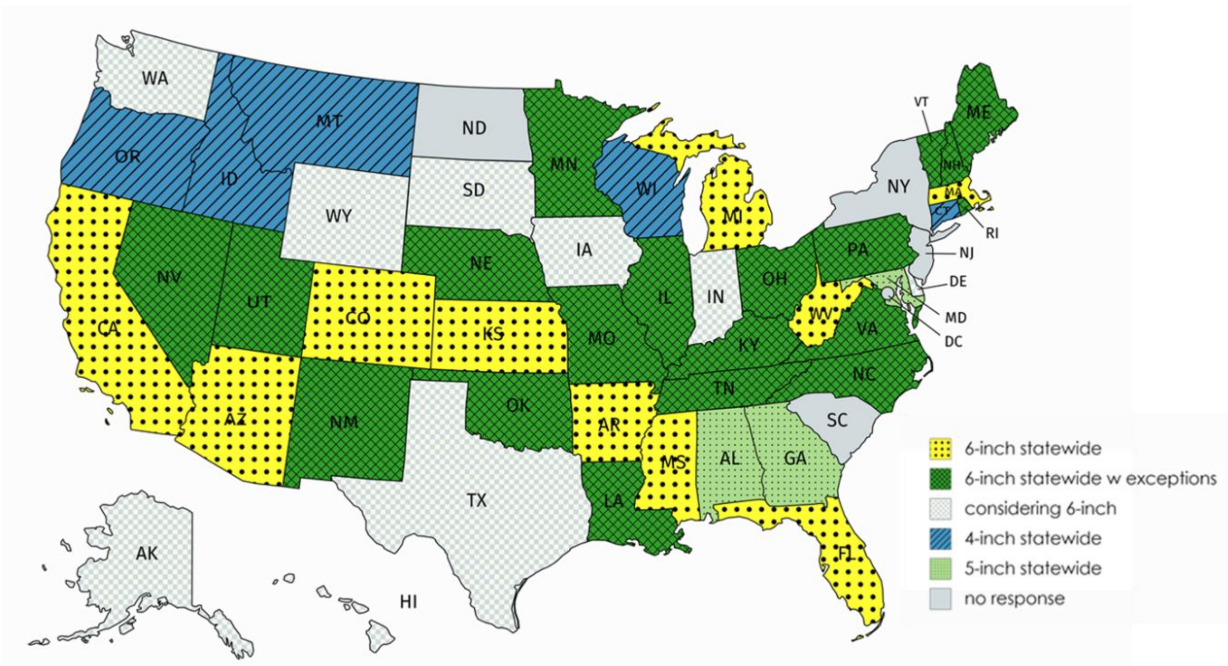

Figure 4. Map. Widths of longitudinal pavement markings across States (as of 2020).

2.1.2. Longitudinal Pavement Marking Daytime Maintenance

A pavement marking characteristic that is not often specified or measured is a metric for daytime visibility even though there is an established test method and available equipment (i.e., luminance coefficient under diffuse illumination, Qd)[3]. Daytime visibility of markings is generally

[3] The luminance coefficient (Qd) is more commonly found in European specifications compared to North America specifications. A similar metric that has also been evaluated in testing forward-looking camera performance is the brightness component of the CIE xyY color space, where chromaticity is defined with x and y and brightness is defined with Y. Generally, the CIE Y metric is a lab measurement used for quality control while Qd is not often used but when it is used, it is more often used in-situ conditions to assess marking performance. There is not an in-service performance standard for either Qd or CIE Y.

thought to be adequate if the marking has enough presence that the human vision system can see and track it. However, machine vision systems do not have the same situational awareness that humans have and are much more reliant on having adequate visibility of pavement markings. Therefore, the daytime visibility, usually measured in contrast to the adjacent pavement surface, becomes quite important for the detection of camera-based system.

In a 2010 report from Sweden, the necessary Qd for dry daytime conditions was reported to be at least 5 mcd/lux/sq-m higher than the road surface and that Qd needs to be at least 85 mcd/lux/sq-m (*12*). In a National Cooperative Highway Research Program (NCHRP) study, the ratio of the luminance (CIE Y), which can be considered an alternative to Qd, was used and a reported threshold ratio of 2.8 provided adequate machine vision detection (*7*). The most recent study, reported in 2020, shows that a minimum ratio of 3:1 is adequate in most conditions. For reference, the Qd of asphalt is typically 40 to 50 mcd/lux/sq-m and concrete is 55 to 75 mcd/lux/sq-m, depending on the age of the roadway and the color of the aggregate used (*9*) and a common Qd range for white pavement markings in a good state of repair tend to be 180-220 mcd/lux/sq-m. The European Union Road Federation has recommended minimum maintained contrast levels of 3:1 with a preferred level of 4:1 (*13*).

2.1.3. Longitudinal Pavement Marking Nighttime Maintenance

Minimum pavement marking retroreflectivity levels for the human vision system have been discussed and researched for decades. With machine vision systems (forward-looking cameras and their companion software) becoming more prevalent in the vehicle fleet, several research efforts have explored the retroreflectivty needs of the camera-based technologies. In an NCHRP study on a closed-course test track, a retroreflectivty level of 34 mcd/sq-m/lux was found to be adequate for most dry nighttime conditions and a level of 4 mcd/sq-m/lux was found to be adequate for wet nighttime conditions (*7*). A Swedish in-situ study found that dry nighttime conditions needed 70 mcd/sq-m/lux, and wet nighttime conditions needed 20 mcd/sq-m/lux (*12*). An Australian report found machine vision systems need a nighttime contrast level between 5-to-1 and 10-to-1 (between the markings and adjacent substrate). For reference, asphalt can measure 5 to 15 mcd/sq-m/lux and concrete can measure 15 to 25 mcd/sq-m/lux (*9*). Therefore, this research recommends roughly 75 mcd/sq-m/lux on asphalt and 150 mcd/sq-m/lux on concrete. The European Union Road Federation has recommended maintaining dry retroreflectivity to a minimum level of 150 mcd/m^2/lx while maintaining wet-recovery retroreflectivity to a minimum level of 35 mcd/m^2/lx (*13*).

In a novel research effort, research from Norway explored whether in-vehicle cameras used for ADAS functions could be used to assess pavement marking condition in lieu of retroreflectivity measurements (*26*). In this effort, an in-vehicle lane departure warning system was compared to data collected simultaneously from an externally mounted mobile retroreflectometer. The test, performed over 200 km of driving on three different routes in variable lighting conditions and road classes found that, depending on conditions, the retroreflectometer could predict whether the vehicle's lane departure systems would detect markings in 92 to 98 percent of cases. The test demonstrated that automated driving systems can be used to monitor the state of pavement markings and can provide input on how to design and maintain road infrastructure to support automated driving features.

2.1.4. Dotted Edge Line Extensions along Ramps

As machine vision systems track markings to position the vehicle, one of the geometric features that can be problematic is exit ramps without dotted edge line extensions. Without the dotted edge line extension, vehicles track the lane line and diverging edge line of the ramp. In this case, the machine vision system sees a lane that is progressively getting wider and the vehicle is then positioned in the center of the diverging lines, usually straight into the gore area. In order to avoid this, the AV developer community has requested dotted edge lines across all exit ramps. Most of this engagement is not formally reported but has occurred through a series of engagements with the NCUTCD CAV Task Force and the AV developers. As a result of these engagements, the NCUTCD recommended specific changes to the US MUTCD. The proposed US MUTCD now includes requirements for dotted edge lines along all exit and entrance ramps (see Figure 5).

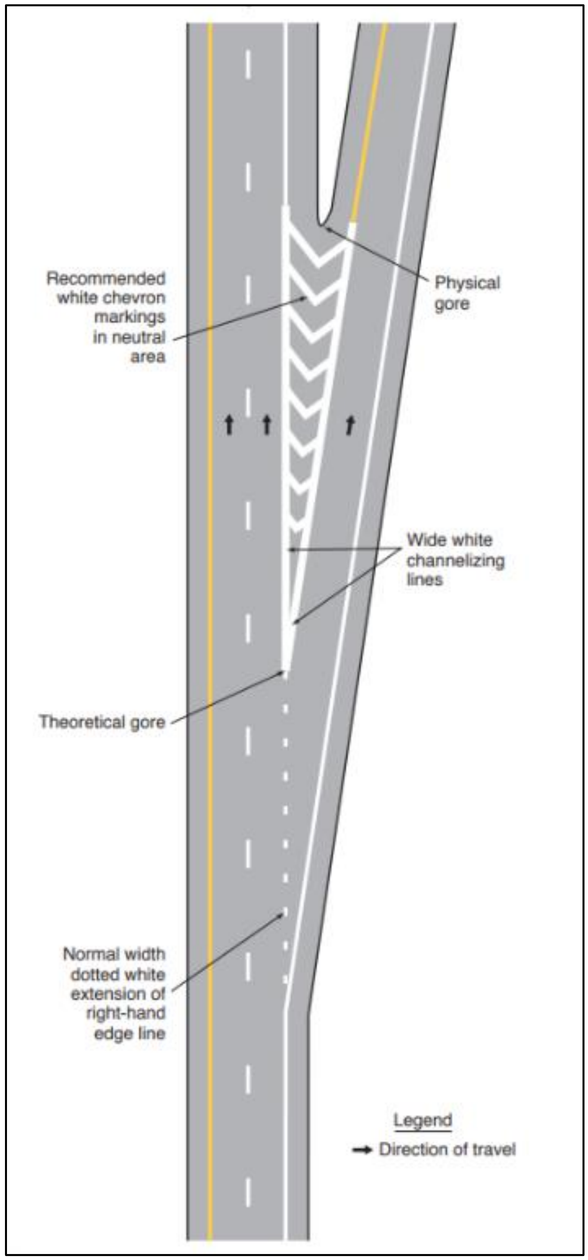

Figure 5. Dotted edge line extensions

2.1.5. Continuous Markings versus Intermittent Markings

Also resulting from the NCUTCD CAV Task Force engagements was a discovery that machine vision systems provide much more reliable results when continuous markings are used compared to intermittent markings. In some places within the US, intermittent markings (usually 4-inch round ceramic or plastic domes) to replicate lane lines and in some temporary applications such as work zone lane shifts. The proposed US MUTCD has eliminated the use of intermittent markings as a substitute for markings (*11*). California adopted the same policy in 2018 (*15*).

2.1.6. Contrast Markings

Sometimes black markings are used to add contrast to white markings when they are used on concrete. There are no known standards that specify contrast marking patterns and as a result, there are several in use. Again, going back to consistency of application, the AV developer community has recently requested that a standard pattern be used. Of the two most common contrast marking patterns (see Figure 6), the stated preference has been the lead-lag pattern due the width of the black contrast marking, making it detectable at longer distance than the two narrow black stripes that make up the oreo pattern (*16*). The lead-lag pattern provides four times more detection distance for today's machine vision systems than the oreo pattern (*16*).

"Oreo" Pattern **"Lead-Lag" Pattern**

Figure 6. Common Contrast Marking Patterns

The 2019 NCUTCD survey of the automotive industry resulted in the same recommendation for contrast markings. In the image below, the contrast markings were added to show how automotive prefers them to be marked.

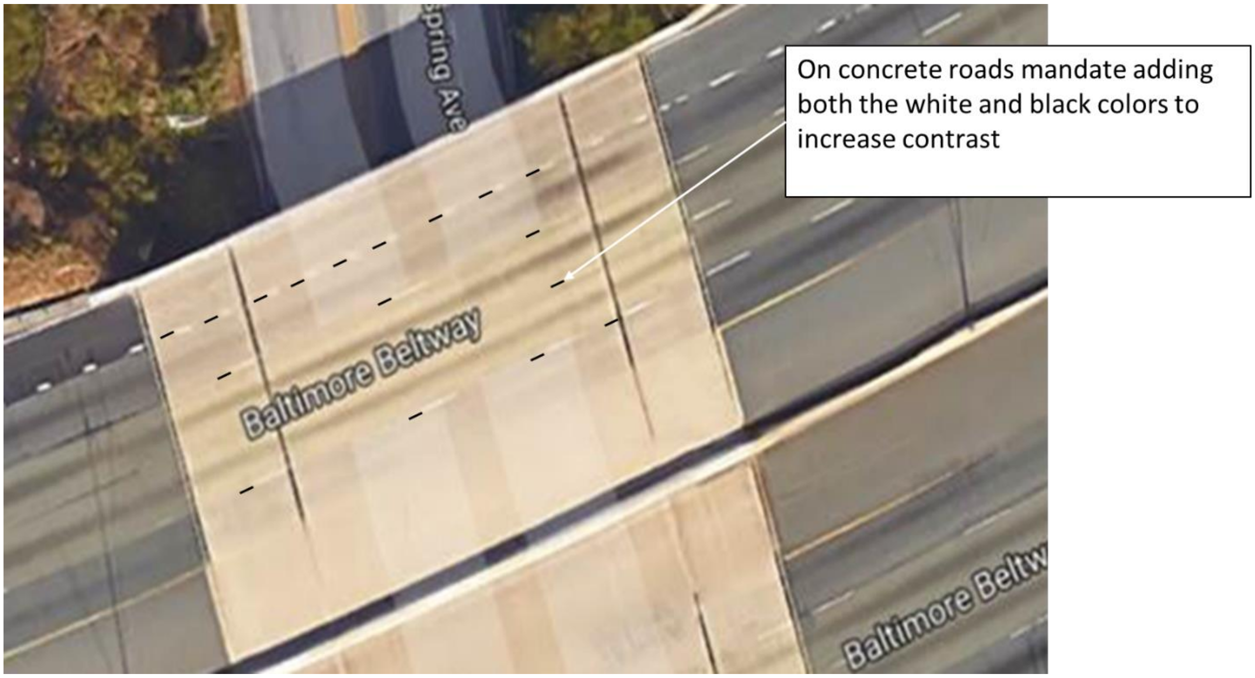

Figure 7. Preferred Contrast Marking Patterns

An on-going research study is also evaluating contrast markings with a primary focus on human vision but the research is also evaluating the implications of contrast marking dimensions on machine vision technology (*17*). This study is scheduled to be completed in June 2021.

2.1.7. Edge Lines versus Curbs

Many roads use curbs as an indicator of the right-hand side of the travel lane. Curbs and other features have lower contrast than a white edge line pavement marking. Feedback from a previous survey suggests that when a lane line is present, such as in the examples below, it would be ideal to include an edge line (*18*). No other information was provided to understand if this only applies to multilane roads or not.

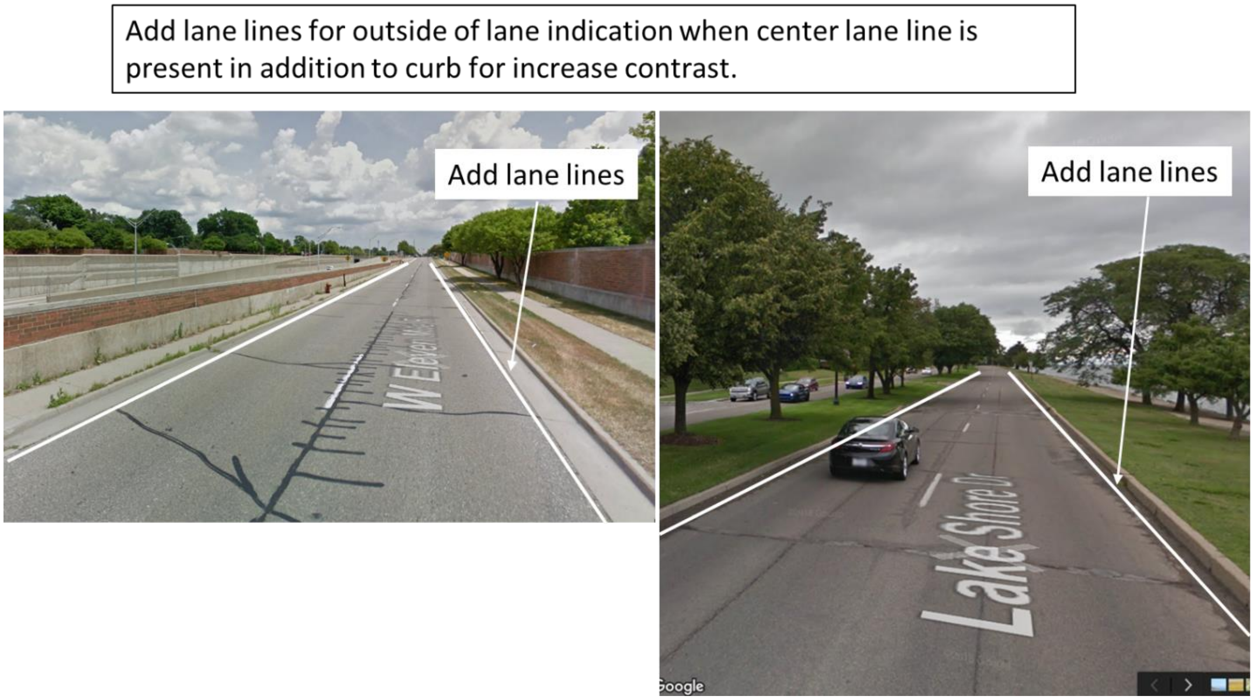

Figure 8. Edge Lines on Multilane Roadways with Curb and Gutter

2.2. Traffic Signs

Although traffic signs are often mentioned in general discussions regarding how TCDs can support AV deployment, there is not as much specific information available as there is for pavement markings. Mostly, the signing-related discussions can be linked to consistent application of traffic signs as well as their support in terms of localization within a digital infrastructure environment (which is outside the scope of this report) (*3*). One issue that has yet to be addressed is bilingual signs. In Canada, English/French signs exist in certain areas while other bilingual signs (such as English/Spanish in the US) exist in and in other parts of the world.

2.2.1. Consistency in placement and use

The request that is most often mentioned in terms of traffic sign applications is consistency with respect to application. The Alliance for Automotive Innovation (then called the Alliance of Automobile Manufacturers) provided comments to the 2018 FHWA RFI stating that it would be helpful if signs were installed and maintained consistently without providing additional information regarding specifics (*2*). In addition, it was also requested that signs be installed on both sides of the roadway more often and in standardized locations. Also, where there are different speeds for different lanes (either variable or static), that a uniform approach is needed to distinguish the speed limit for each lane.

One of the more common signs that AVs look for and read is a speed limit sign. In that regard, there have been several requests that speed limit signing be more standardized in terms of location and maintenance. Also, in conditions with parallel roads (such as freeways with frontage roads), there can be confusion regarding which roadway the speed limit signs posted between the roadways apply to.

2.2.2. Light Emitting Diode (LED) signs

As LED technology has been introduced to traffic signs, it has been designed for the human visual system to which it which provides the appearance of continuous operation even though the LEDs are flashing at an undetectable rate. As vehicle cameras become more common, an issue has developed where the vehicle camera may operate at a frequency different than the signs, or elements within the sign. The uncoordinated frequency of the LED signs and vehicle cameras can create scenarios where LED signs and LED signals are not initially detected or fully readable. Examples are provided below. Furthermore, there is no current standard for operating a vehicle camera at a specific frequency or within a specific range. In 2019, a recommendation was made that LED signs operate at 200 Hz or greater (*18*). The proposed US MUTCD has language now that includes the 200 Hz or greater statement (*11*). A just completed survey of the AV industry has also included a recommendation that LED signs operate at 200 Hz (24).

a.	b.

Figure 9. LED Flicker Issue (a. both signals are lit and red to human vision b. the sign is fully and uniformly lit to human vision

2.2.3. Embedded Code signs

In 2017, the company 3M and the Michigan DOT deployed experimental signs, for 100 days, with embedded coding that was only detectable using an infrared (IR) emitter and receiver. The embedded coding was designed to provide supplemental information to vehicles equipped with an aftermarket 940 nm IR-camera system (*19-20*). In practice, the embedded barcode signs were captured and processed by the aftermarket IR system on equipped vehicles passing the signs. The embedded barcode technology could theoretically be used for a variety of applications, but no immediate needs have been identified and it has not yet been commercialized.

2.2.4. School Signs

In the NCUTCD's 2019 survey, many specific school sign requests were made by the automotive industry (*18*).

- Design – All school speed limit signs should have a yellow "SCHOOL" sign affixed directly above a speed limit sign. If there are conditional School signs (for example, "When Children

Are Present), the content of the text should be standardized. All end school zone signs should display the text “END SCHOOL ZONE” with no other additional text.

- Shape – All school speed limit signs should be consistent in shape and have the same dimensions (standard length and width).
- Illumination – If the speed limit value of a school sign is to be illuminated, it should have a standard refresh/flicker rate. The refresh rate of the LEDs should be greater than 200 Hz to be easier for the camera to detect.

2.2.5. Other Signs

Unless otherwise noted, the information below comes from the NCUTCD’s 2019 effort to survey the automotive industry in terms of the needs of TCDs to support AV deployment (*18*).

- Many agencies have additional road signs which are not included in the MUTCD. For example, the State of California implements road signs for speed zone ahead or ending of a certain speed limit which are not covered by the MUTCD. These road signs, as well as many other unique road signs in various States, should also be included in the consideration by the committee for a development of uniformity recommendation.
- For any Yield Here to Pedestrian signage, ensure there is a stop line or yield demarcation accompanied with it.
- The AV industry is interested in having roadway agencies report temporary or moved traffic control signs (e.g, stop sign, temporary traffic signal); or a new sign or message easily perceived by AVs to recognize such. This specific topic is more related to digital maps and not specifically TCDs but it is included herein because it has been a common request and is somewhat TCD-related.
- Overall, the AV industry would prefer that roadway agencies communicate new traffic signage with reasonable lead time and provide a nation-wide database with traffic signs and their positions (24).

2.3. Traffic Signals

Unless otherwise noted, the information below comes from the NCUTCD’s 2019 effort to survey the automotive industry in terms of the needs of TCDs to support AV deployment (*18*).

- More uniformity in traffic signal placement would be helpful. Particularly problematical are horizontal traffic signals.
- Traffic lights should be standardized for the entire country including: Position, location, color, shape, refresh rate (greater than 200 Hz).
- East and West routes would benefit from back plates, particularly in low sun conditions.
- The traffic lights should have a clear, unambiguous association with the specific lanes.
- Traffic signals employing optical programming and mechanical louvers to limit field-of-view can be difficult to detect by ADS technologies, and their use should be limited. If strictly necessary, mechanical louvers are preferred to optical programming (24).

- All steps should be taken to standardize high and low brightness for traffic signal heads, as well as ensure sufficiently large traffic signal head sizing. A 12-inch diameter is preferred over 8-inch diameter (24).
- Implement standardized and sufficient distance separation of traffic lights that target different classes of vehicles. For example, avoid locating cyclist, bus, and automotive traffic lights so close together that confusion between them can be made at a distance (24).
- Ensure that traffic lights are standardized to be located at the end of an intersection. Some intersections only have lights at the beginning of the intersection and no signal at the far end (24).
- Avoid flashing beacons where a green light can be used. For example, a pedestrian crossing controlled by a HAWK beacon would be much better as a pedestrian-controlled standard green-yellow-red light. Generally, any light for which "off" means "go" can create ambiguities for an ADS due to visual impediments. Both "stop" and "go" directives should be explicit (from the presence of a signal) rather than implicit (from the absence of a signal) (24).

2.4. Work Zone TCDs

Unless otherwise noted, the information below comes from the NCUTCD's 2019 effort to survey the automotive industry in terms of the needs of TCDs to support AV deployment (*18*).

- All construction zones should have standard traffic signs that warn the driver of an upcoming construction zone (e.g., Construction Site in ½ Miles).
- The end of a construction zone should be indicated by a clear standardized sign.
- Construction sites/road work should be clearly marked with orange markings that remain at their place throughout the duration of construction if there is a situation where the construction project has caused an absence of clear and visible lane markings for an extended period of time. These markings also shall be visible in rain or when run over to allow for good lane-keeping guidance.
- Narrow lanes need to be signed in advance with a standard sign.
- Beacons/cones/barrels on construction sites should be equipped with good reflective materials/stickers and with a sufficient size for a good detection rate by computer vision even in rain and at night.
- Standardize the shape and size of the above beacons/cones/barrels/narrow lane signs.
- The wide variety of construction zone signs is problematical for ADS-operated vehicles (low contrast, variable text). They are especially difficult to "read" in low ambient lighting conditions or rain. Moving to pictorial signs with higher contrast would be helpful.
- Uniformity in the setup and signage of construction zones would also be very helpful for ADS-operated vehicles.
- Intermittent markings should not be used in construction zones. Construction zones should always use continuous markings, preferably not occluded by other work zone devices such as cones or barrels.
- Channelizing devices such as small diameter poles are difficult for cameras to detect. A minimum width of 6 to 8 inches is preferred, with reflective tape (24).

The proposed US MUTCD has new provisions for construction zones as well (*11*). The key provisions are shown below. These provisions are provided by the FHWA to help agencies understand how to begin to prepare their roadways for AV deployment.

Section 5B.04 Temporary Traffic Control

To better accommodate machine vision used to support the automation of vehicles, channelizing devices should be at least 8 inches wide with retroreflective material for reliable machine detection in all weather conditions. Markings entering the work zone and through lane shifts should be made with highly visible and continuous materials, not intermittent buttons and reflectors.

2.5. Summary

As demonstrated above there is a growing amount of information available to understand how the TCD infrastructure can support AV deployment. However, the information for specific TCD types and TCD characteristics is not equally mature or understood. Therefore, this summary attempts to categorize the information into three areas: convergence, divergence, and insufficient information.

2.5.1. TCD Topics with Converging Information

The need to tighten TCD uniformity within certain aspects of the TCD infrastructure space is perhaps the most common request among AV developers. In that regard, there is a growing body of knowledge that can be useful to agencies interested in preparing their highways for AV deployment. The areas that appear to have consensus with supporting research, AV industry input, and/or infrastructure industry support are listed below.

- Pavement markings
  - Using 6-inch wide longitudinal markings on freeways and Interstate highways
  - Using dotted edge line extensions along ramps
  - Using 6-inch edge line markings on conventional highways
  - Using continuous markings (over intermittent markings using buttons and markers) while entering work zones and along lane shifts
  - Eliminating the practice of substituting markings with buttons
  - When used, specifying the lead-lag contrast marking pattern
  - Maintaining a daytime contrast ratio of at least 3:1 (using Qd as metric).
- Traffic signs
  - Improving consistency of speed limit sign applications (locations)
- Work Zones
  - Using a minimum of 8-inch wide channelizing devices

2.5.2. TCD Topics with Diverging Information

As demonstrated by the FHWA RFI of 2018, another common request from AV developers is maintaining markings and signs in a good-state-of-repair. While there have been attempts to define nighttime maintenance needs from a machine vision perspective, there does not appear to be strong consensus regarding the findings. Specific TCD areas have been researched multiple times but the results do not appear to be aligned. A list of TCD topics with diverging information is provided below.

- Pavement Marking Maintenance Criteria
  - Maintained retroreflectivity levels for machine vision – the research findings related to the retroreflectivity levels needed for machine vision detection are not consistent and vary significantly. The lack of convergence regarding research findings is true for both dry and wet nighttime conditions.

2.5.3. TCD Topics with Insufficient Information

While progress in the AV space is moving forward, it is still in the infancy stage of its full life cycle. As a result, there are many items where the amount of information is incomplete or just now developing. Of the TCD topics that have been documented, the list below includes those where there is insufficient information to classify into one of the previous two categories.

- Pavement Markings
  - Edge lines versus curbs – this topic was introduced within the FHWA RFI of 2018 but has not surfaced since.
- Traffic Signs
  - LED Signs – while the proposed US MUTCD has provisions for LED signs, the IEEE-SA P2020 - Automotive Image Quality Working Group, which includes vehicle camera manufacturers and OEMs, is working toward a standard for vehicle cameras that may address the current inconsistencies.[4]
  - Embedded Code Signs – The Michigan DOT trial demonstrated the functionality of embedded code but a specific need and further testing is needed.
  - School Signs – the suggestions related to School signs were introduced within the FHWA RFI of 2018 and have not surfaced since.
  - Other Signs – the suggestions related to other signs were introduced within the FHWA RFI of 2018 and have not surfaced since.
  - Retroreflectivity – the brightness of signs related to machine vision systems has not been evaluated to the same extent that pavement markings have. Anecdotally, comments have been made at various meetings supporting both extremes—signs should be brighter and signs can be too bright for the camera systems.
- Traffic signals
  - The NCUTCD CAV Task Force has started to engage with the AV developers to better understand how traffic signal practices may be enhanced to support machine vision. The current item that seems to have some momentum is the use of back plates on intersection approaches facing East and West – where the sun can be in low positions behind the signals, causing difficulty in signal detection and reading.

[4] https://site.ieee.org/sagroups-2020/

- Work Zone TCDs
    - Most of the work zone suggestions listed earlier were obtained through a NCUTCD CAV Task Force survey of the automotive industry. Since then, there has been continued dialogue with the AV developer community. Several items have been resolved such as the width of channelizing devices and the need for continuous markings in lane shifts and tapers. However, there is still a broad need to tighten uniformity within work zone layouts and digitally locate work zones for AV applications. The FHWA has also been working for several years on the "Work Zone Data Exchange" to enables highway agencies to make harmonized work zone data available for third party use (*21*).

3. Agency Policies and Practices

In the US, there are several agencies that have already started to make policy changes to prepare their roadways for AVs. The proposed MUTCD, which was just released in December 2020 could produce a more uniform approach, depending on the final version. An on-going NCHRP study surveyed the US DOTs to determine how they have been preparing for AV deployment (*22*). Some of the key findings from the survey are described below.

- California: Starting in 2018, California adopted 6-inch wide pavement markings in addition to eliminating the use of buttons as a substitute for lane lines. They also started to specify more durable markings (such as thermoplastic and methyl-methacrylate or MMA at elevations above 3,000 ft).
- Colorado: Developed a statewide plan to upgrade their markings to 6-inch wide.
- Kentucky: Adopted 6-inch wide pavement markings for their primary highways.
- Michigan: expanded the use of 6-inch wide markings throughout the state.
- New Hampshire: In addition to using 6-inch markings, added dotted edge line extensions across ramps.
- Washington: Adopting 6-inch markings in Eastern half of state and 4-inch high-build waterborne paint markings in Western half of state.
- Iowa: Adopting 6-inch markings for their primary highways. Lane lines will be grooved in to prolong life of markings due to snow operations.

4. Agency Concerns

In 2019, the FHWA held two workshops to gather agency feedback on highway readiness ideas, including enhancing the TCD infrastructure (*5*). The events were held at the American Association of State Highway and Transportation Officials (AASHTO) Committee on Maintenance Workshop in Grand Rapids, MI, on July 17, 2019, and the Automated Vehicle Symposium in Orlando, FL, on July 18, 2019.

Many of the state DOT participants of these workshops stated that their agency lacked the funding needed to prepare their highways for AVs let alone keep their existing assets in a good state of repair, which is similar to the FHWA's RFI findings published in 2018. Recognizing that markings are the rails for AV, some of the participants from the northern climates where winter maintenance activities are frequent stated that markings are already difficult to maintain due to snowplow damage and wondered how that might impact their readiness. Agencies also wondered if technology might supersede some of their efforts to prepare their highways since it might take ten years to upgrade a specific highway asset systemically and in reference to the pace of technology, ten years seems like a long time. Other agencies stated that they preferred to see a robust national strategy be developed that linked any upgrades to the TCD infrastructure to specific timelines associated with the progress and deployment of vehicle automation technology. On the other hand, some agencies reported that they had already started to update their pavement marking policies, including the use of 6-inch wide markings, more durable materials, and more frequent inspection of their markings.

Of all the TCD infrastructure types, pavement markings have the shortest life cycle. In some northern climates, roads are striped annually. In southern areas without snowplow activity, markings can have a much longer life cycle—up to 6 years depending on the material used, traffic volume and mix, pavement conditions, etc. However, signs, signals and many other TCDs have a much longer life cycle—up to 20 years or more. Therefore, pavement markings are probably one of the most economic TCD types to upgrade, at least compared to other traditional categories of TCDs. For instance, adding another 2-inches in width requires more paint and beads but the striping equipment and traffic control is already accounted for in maintenance budgets. The expected costs are nominal since the upgrades can be achieved through routine maintenance as the number of AV-equipped vehicles continues to increase (see Figure 1). In addition, the safety benefit will continue to climb. For instance, research shows that the most common fatal crash type in the US (single vehicle lane departures) can be reduced by as much as 66 percent, depending on the technology adoption rates and roadway readiness levels (*23*). Lastly, there may be a breaking point in the future where agencies reallocate their funding as a result of advances in vehicle technologies and their impact on crash types, frequencies, and patterns. For instance, if lane departure prevention technologies continue to improve to the point that they become reliable with the presence of an edge line pavement marking, then shoulder rumble strips, safety edge, and others countermeasures designed to be effective after a vehicle leaves the road may eventually be less and less effective since fewer vehicles leave the travel lane.

5. Prioritization of TCD Considerations

The topics from the literature review that were classified as having convergence with respect to research findings, AV industry input, and/or infrastructure industry support are listed below.

- Pavement markings
  - Using 6-inch wide longitudinal markings on freeways and Interstate highways
  - Using dotted edge line extensions along ramps
  - Using 6-inch edge line markings on conventional highways
  - Using continuous markings (over intermittent markings using buttons and markers) while entering work zones and along lane shifts
  - Eliminating the practice of substituting markings with buttons
  - When used, specifying the lead-lag contrast marking pattern
  - Maintaining a daytime contrast ratio of at least 3:1 (using Qd as metric).
- Traffic signs
  - Improving consistency of Speed limit sign applications (locations)
- Work Zones
  - Using a minimum of 8-inch wide channelizing devices

In developing a framework to prioritize possible TCD enhancements as listed above, key factors such as impact, effort, and weather were considered. Each of the factors is explained below, including sub-elements within the factors. The prioritization criteria that were used to make an initial assessment are also described along with the scores assigned (in parenthesis). The results of the possible prioritization framework are shown in Table 1. **This exercise is meant to be an example of a process that could be used to prioritize the options and is not meant to be definitive.**

- Impact – how much support is there for the specific TCD enhancement in terms of AV deployment as well as human-led safety
  - AV Operations
    - High (3)
      - Research findings available to support TCD provision
      - Demonstrated DOT support such as implementation
    - Medium (2)
      - 1 of 2 criteria satisfied
    - Low (1)
      - Does not meet either criteria
  - Human-led safety
    - High (3)
      - Research findings available to support TCD provision
      - Demonstrated DOT support such as implementation
    - Medium (2)
      - 1 of 2 criteria satisfied
    - Low (1)
      - Does not meet either criteria

- Effort – a way to prioritize the effort necessary to make the change in terms of cost and time
    - Cost – relatively, how much would it cost to make the TCD enhancement
        - High (1)
        - Medium (2)
        - Low (3)
    - Time – how long would it take to systemically implement the provision given the life cycle of the TCD in respect to the facility type
        - Long – will probably take more than 3 years (1)
        - Moderate – could take 2 to 3 years (2)
        - Quick – could be implemented within one full season (3)

- Availability – how available is the TCD provision given the winter conditions in Canada
    - Practically all of the time (3)
    - Most of the time, except when covered with snow (2)
    - Some of the time, depending on snow removal practices (1)

Table 1. Example: TCD Enhancement Prioritization Framework

Specific TCD Considerations	Impacts		Effort		Availability	Score
	AV Operation	Human-led safety	Cost	Time		
Using 6-inch wide longitudinal markings on freeways and Interstate highways	H	H	M	M	H	12
Using dotted edge line extensions along ramps	M	M	L	M	M	11
Using of 6-inch edge line markings on conventional highways	H	H	H	L	M	12
Using continuous markings (over intermittent markings using buttons and markers) while entering work zones and along lane shifts	M	M	M	L	M	11
Eliminating the practice of substituting markings with buttons	M	M	N/A	N/A	L	N/A
When used, specifying the lead-lag contrast marking pattern	M	M	L	L	M	12
Maintaining a daytime contrast ratio of at least 3:1 (using Qd as metric).	M	L	H	H	M	7
Improving consistency of Speed limit sign applications (locations)	L	L	M	H	H	8
Using a minimum of 8-inch wide channelizing devices	L	L	H	M	H	8

6. Topics of Possible Research

Research needs were derived from the summary of the literature review. Primarily, items where there was not enough alignment within the current body of knowledge to move forward. These research statements described below should be useful in providing new information that can be used by agencies to operate and maintain roads in a way that will support AV technologies.

6.1. Research Need 1: Machine-Vision Standards for TCDs

Background

TCD standards regarding size, color, and daytime and nighttime appearance have been developed based on human capabilities, including the capabilities of older drivers. Existing standards are scattered throughout various sources, such as the MUTCD, CFR, ASTM, National Electrical Manufacturers Association (NEMA), Institute of Transportation Engineers, and AASHTO. Researchers developed NCHRP 20-102(6) to investigate how pavement-marking standards could be updated to support machine-vision systems. More work is needed. For example, TCDs with LEDs are becoming more popular; however, some AV sensors cannot read them because the LEDs in the TCDs operate at a different Hertz frequency than the equipment in the vehicle. Ongoing research in Europe is starting to demonstrate how sensitive AV sensors, such as passive cameras and LiDAR sensors, are to pavement-marking color.

Objectives

The objective of this research is to determine if TCD standards need to be updated to accommodate AV sensors and if so, how. The research would include an inventory of the existing TCD appearance-related standards across all sources National and Local policies, an assessment of the sensors used on AVs today, including their capabilities, and a thoughtful look at the future regarding timelines of existing sensors and their evolution as well as sensors likely to be included in technology suites for AVs.

Potential Benefits

Part of understanding road readiness is determining if the TCDs that have been designed to accommodate human vision are adequate for machine vision. While tightening uniformity is perhaps the first step (research needed), another step is synchronizing TCDs so that they are visible to both human- and machine-vision systems. LED-based TCDs are everywhere, from traffic signals to dynamic message signs, and they are critical for roadway safety.

6.2. Research Need 2: Informing AV Test Scenarios with Representative Infrastructure Conditions

Background

Current testing of existing AV technologies, such as lane-departure prevention systems, is conducted under ideal conditions with high-contrast markings in pristine condition.[5] In addition, current testing is conducted with uniform and dry pavement as well as clear and dry weather. These protocols are often not representative of real-world driving conditions and the state of TCDs and infrastructure. There is on-going work within the UN Working Party 29 that has started to develop AV Test Scenarios.

Objectives

The objectives of this research are to help inform testing conditions for AV technologies that are representative of the existing roadway network on which those AV technologies are expected to be used. For instance, if the AV technology is meant to work on divided highways, then the testing of those technologies should be performed with conditions that represent the existing state of repair

[5] An example test procedure for Lane Departure Warning: https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/812078_heavy-vehiclelanedepartwarntestdevelmt.pdf

of those highways. This research should include testing factors (e.g., day/night and sunny/cloudy) and changing environmental factors, such as rain, fog, and snow.

Potential Benefits

Establishing realistic expectations of AV-technology performance may help the public in terms of understanding and accepting AVs. In addition, there is a growing need to develop robust expectations of how AV technologies will impact fatal and serious injury crashes. Conducting tests of these technologies with realistic scenarios will help researchers and agencies prioritize their focus in the most cost-effective ways.

6.3. Research Need 3: Understanding the Effectiveness of Lane Marking Enhancements

Background

One of the most common recommendations within the TCD infrastructure to support AV deployment is pavement markings. The current ADAS-equipped vehicles and future ADS vehicles will be designed to detect and track markings. Research has shown that 6-inch wide markings provide more robust detection than 4-inch wide markings but there remain questions about the tradeoff (cost versus benefit), maintenance levels, and environmental conditions such as those representing northern climates prone to snow and winter maintenance activities.

Objectives

The objective of this research would be to further evaluate a systemic transition to 6-inch wide markings considering the cost to upgrade the marking width versus the expected crash reduction, including both human led vehicles and AVs. The research should include a timing aspect as well, focused on fleet penetration of the appropriate AV technology. In addition, the research approach needs to consider the harsh climate that is indicative of northern climates prone to snow and winter maintenance activities. What minimum levels of presence, contrast, and retroreflectivity are needed for the vehicle systems to be robust enough to provide reliable detection and therefore crash reduction benefits.

Potential Benefits

Road agencies are trying to better understand specific benefits of suggested enhancements within the TCD infrastructure to support AV deployment. This research is designed to provide answers to some of the remaining questions regarding pavement markings enhancements.

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