Needs Statement 562 – Pavement Markings for Autonomous Driving: Literature Search

Wednesday, June 26, 2019

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Resources searched: Library catalog, ASCE Database, TRID, Rip, Transport Database, Web

Summary: Results are compiled from the databases named above. Links are provided for full-text, if applicable, or to the full record citation. I completed my searches using the following terminology: autonomous driving systems, autonomous vehicle, pavement marking, lane marking, road marking, and standards. The results below are divided into the categories of most relevant and least relevant results.

Most Relevant Results

Research in Progress

Pavement Marking Patterns and Widths – Human Factors Study
The principal focus of this study is to investigate appropriate pavement marking dimensions and contrast with respect to human vision and driver comfort. As a secondary effort, this research will also evaluate the implications of pavement marking dimensions on machine vision technology that is used in Advanced Driver Assistance Systems (ADAS) and automated vehicles (AVs). The results of this study will provide insight as to how MnDOT can effectively leverage its resources to provide pavement markings that effectively meet the needs of all road users.

Language
  o English

Project
  o Status: Programmed
  o Contract Numbers: 1003324 WO#7
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    395 John Ireland Boulevard
    St Paul, MN United States 55155
  o Performing Organizations: Texas A&M Transportation Institute, College Station
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  o Principal Investigators: Pike, Adam
  o Start Date: 20190701
  o Expected Completion Date: 0
  o Actual Completion Date: 0

Subject/Index Terms
  o TRT Terms: Autonomous vehicles; Driver support systems; Lane lines; Road markings
  o Subject Areas: Pavements; TRAFFIC CONTROL;

Filing Info
Road Curb and Lanes Detection for Autonomous Driving on Urban Scenarios
Fernandez, C; Izquierdo, R; Llorca, D F; Sotelo, M A
Abstract. This paper addresses a framework for road curb and lanes detection in the context of urban autonomous driving, with particular emphasis on unmarked roads. Based on a 3D point cloud, the 3D parameters of several curb models are computed using curvature features and Conditional Random Fields (CRF). Information regarding obstacles is also computed based on the 3D point cloud, including vehicles and urban elements such as lampposts, fences, walls, etc. In addition, a gray-scale image provides the input for computing lane markings whenever they are present and visible in the scene. A high level decision-making system yields accurate information regarding the number and location of drivable lanes, based on curbs, lane markings, and obstacles. The authors' algorithm can deal with curbs of different curvature and heights, from as low as 3 cm, in a range up to 20 m. The system has been successfully tested on images from the KITTI data-set in real traffic conditions, containing different number of lanes, marked and unmarked roads, as well as curbs of quite different height. Although preliminary results are promising, further research is needed in order to deal with intersection scenes where no curbs are present and lane markings are absent or misleading.

Reading the Road: Road Marking Classification and Interpretation
Mathibela, Bonolo; Newman, Paul; Posner, Ingmar
Abstract. Road markings embody the rules of the road whilst capturing the upcoming road layout. These rules are diligently studied and applied to driving situations by human drivers who have read Highway Traffic driving manuals (road marking interpretation). An autonomous vehicle must however be taught to read the road, as a human might. This paper addresses the problem of automatically reading the rules encoded in road markings, by classifying them into seven distinct classes: single boundary, double boundary, separator, zig-zag, intersection, boxed junction and special lane. The authors' method employs a unique set of geometric feature functions within a probabilistic RUSBoost and Conditional Random Field (CRF) classification framework. This allows us to jointly classify extracted road markings. Furthermore, the authors infer the semantics of road scenes (pedestrian approaches and no drive regions) based on marking classification results. Finally, their algorithms are evaluated on a large real-life ground truth annotated dataset from their vehicle.
Precise Localization of an Autonomous Car Based on Probabilistic Noise Models of Road Surface Marker Features Using Multiple Cameras

Jo, Kichun; Jo, Yongwoo; Suhr, Jae Kyu; Jung, Ho Gi; Sunwoo, Myoungho

Abstract. This paper presents a Monte Carlo localization algorithm for an autonomous car based on an integration of multiple sensors data. The sensor system is composed of onboard motion sensors, a low-cost GPS receiver, a precise digital map, and multiple cameras. Data from the onboard motion sensors, such as yaw rate and wheel speeds, are used to predict the vehicle motion, and the GPS receiver is applied to establish the validation boundary of the ego-vehicle position. The digital map contains location information at the centimeter level about road surface markers (RSMs), such as lane markers, stop lines, and traffic sign markers. The multiple images from the front and rear mono-cameras and the around-view monitoring system are used to detect the RSM features. The localization algorithm updates the measurements by matching the RSM features from the cameras to the digital map based on a particle filter. Because the particle filter updates the measurements based on a probabilistic sensor model, the exact probabilistic modeling of sensor noise is a key factor to enhance the localization performance. To design the probabilistic noise model of the RSM features more explicitly, the authors analyze the results of the RSM feature detection for various real driving conditions. The proposed localization algorithm is verified and evaluated through experiments under various test scenarios and configurations. From the experimental results, the authors conclude that the presented localization algorithm based on the probabilistic noise model of RSM features provides sufficient accuracy and reliability for autonomous driving system applications.

Best Practices Guidebook for Preparing Texas for Connected and Automated Vehicles

Kockelman, Kara; Loftus-Otway, Lisa; Stewart, Duncan; Nichols, Aqshems; Wagner, Wendy; Li, Jia; Boyles, Steve; Levin, Michael; Liu, Jun

Abstract. Connected and automated vehicles (CAVs) are destined to change how the Texas transportation system operates. Texas Department of Transportation (TxDOT) is responsible for the nation’s most extensive state-level network, and it is essential to explore the potential impacts of CAVs on the design, maintenance, and operation of the transportation system. Research into CAVs’ mobility, environmental, legal, and safety implications for the state of Texas was conducted by University of Texas (UT) Austin’s Center for Transportation Research (CTR). This document presents the main points of CTR’s research on CAVs and develops practice recommendations, emphasizing safety, to assist TxDOT in optimally planning for these new technologies using a holistic and qualitative approach. The current state of maturity of existing and developing CAV technologies is assessed here to provide recommendations for TxDOT to pursue
in the short term (next 5 years), medium term (five to fifteen years), and long term (15+ years). Identified strategies include pavement-marking updates, improving signage standards, modifying design manuals, shaping legislative policy on autonomous vehicles (AVs), and establishing rules for shared AV (SAV) use, along with other options. The guidebook is divided into five sections: (1) Overview of CAV Technologies; (2) The Current Texas Legal Landscape for CAVs; (3) Potential Benefits Using CAV Technologies; (4) Potential Safety Strategies for TxDOT to Adopt to Prepare Texas for CAV Use; and (5) Best-Practice Recommendations for TxDOT in Deployment of CAVs in Texas.
Recent research with the Oregon Department of Transportation (ODOT) has developed an automated method for extracting linear lane markings from mobile laser scan (MLS) data as well as evaluating the retroreflectivity of those markings. The research team is building upon this effort to develop advanced techniques to handle more complex markings (e.g., pedestrian crosswalks, chevrons, and arrows) that were not considered in the prior project, but are important to support mobility for multi-modal transportation. First, the team projects the MLS data into 2D to generate an intensity image and segment high intensity pixels, likely representing various road markings. Subsequently, a deep learning neural network approach, which is known for its high performance for object recognition in many applications, is used to classify various types of markings. This research will enable performance-based procedures for transportation agencies to evaluate pavement marking quality by providing detailed information, including retroreflectivity and types of markings, ranging from high resolution data on a single stripe to aggregated data and analyses statewide. This, in turn, supports informed decision making by DOT management for effective resource allocation. Improved maintenance of pavement markings will also lead to improved mobility with technologies such as autonomous vehicles.

Least Relevant Results

Research in Progress

TRID Database

Efficient Extraction and Evaluation of Complex Pavement Markings from Mobile Laser Scan Data

Language
- English

Project
- Status: Active
**Subject/Index Terms**
- TRT Terms: Data collection; Information processing; Lasers; Neural networks; Retroreflectivity; Road markings
- Subject Areas: Data and Information Technology; Highways; Maintenance and Preservation; Pavements;

**Filing Info**
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**Abstract.** The typical road infrastructure consists of visual cues, as human drivers predominately use their vision to navigate around and drive their vehicles on the road. In a similar manner, most advanced vehicles today -as well as the ones currently designed for the future- also rely on cameras and sensors that help the vehicle 'see' the world around it. Human drivers will most likely co-exist with Connected Autonomous Vehicles on the roads for many years to come, possibly decades. This paper will look at the importance of designing road markings today for both types of drivers of tomorrow.

**Record Type:** Publication
**Supplemental Notes:** Extended abstract only
**Monograph Title:** Proceedings of the 2018 Australasian Road Safety Conference, 3-5 October, Sydney, New South Wales
Result 1.

**Title**  
GPU Implementation for Automatic Lane Tracking in Self-Driving Cars.

**Source**  

**URL**  
https://doi.org/10.4271/2019-01-0680

**Abstract**  
The development of efficient algorithms has been the focus of automobile engineers since self-driving cars become popular. This is due to the potential benefits from self-driving cars and how they can improve safety on roads. Despite the good promises that come with self-driving cars development, it is way behind being a perfect system because of the complexity of the environment. A self-driving car must understand its environment before it makes decisions on how to navigate, and this might be difficult because the changes in the environment is non-deterministic. With the development of computer vision, some key problems in intelligent driving have been active research areas. The advances made in the field of artificial intelligence made it possible for researchers to try solving these problems with artificial intelligence. Lane detection and tracking is one of the critical problems that need to be effectively implemented. The ability of a self-driving car to successfully drive from point A to point B without going off track is dependent on lane tracking. Lane tracking in self-driving cars is a computationally intensive task and a fast implementation is needed to help a self-driving car track lanes in real-time to make the right decision at the right time. Lane tracking in self-driving cars is also dependent on the visibility of lane markings on the road. It will be difficult for a self-driving car to track lanes if the lane marking has faded, blocked by an object, or there were no lane markings on the road. Most available lane tracking implementations in the literature do not give account to these two problems. The authors' implementation is to solve these two problems by using artificial intelligence techniques to track lanes in all conditions and using GPU computing on NVIDIA Jetson TX2 to speed-up the process.

**Publication Year**  
2019

Result 8.

**Title**  
Fatal Tesla Crash Highlights Risk of Partial Automation.

**Source**  

Abstract This article, from a special issue on autonomous vehicles, describes a fatal crash of a Tesla model X on a Mountain View, California highway in March 2018. The author notes that this case report offers an unfortunate real-world example of the operational limits of advanced driver assistance systems (ADAS) and autonomous vehicles. The system gave the driver two visual alerts and one auditory alert to place his hands on the wheel during the 19-minute period when the driver had the vehicle set on "Autopilot." In the final 6 seconds before impact, his hands weren't detected on the wheel, and the Tesla didn't make any emergency braking or steering maneuvers to avert the crash. Test drives of the Model S by the Insurance Institute for Highway Safety, conducted on public roads, suggest that Autopilot may be confused by lane markings and road seams where the highway splits. The article stresses that other manufacturers' Level 2 vehicles likely have been involved in crashes while drivers were using advanced driver assistance features. Readers are referred to the full National Transportation Safety Board preliminary report on the 2018 Tesla crash in Mountain View, California.

Publication Year 2018

Result 11.

Title Real Time Detection and Classification of Arrow Markings in Urban Streets.


URL http://dx.doi.org/10.1007/s12239-018-0036-x

Abstract For highly automated driving in urban regions it is essential to know the precise position of the car. Furthermore it is important to understand the surrounding context in complex situations, e.g. multilane crossings and turn lanes. To understand those situations there is not only the task to detect the lane border, but to detect the painted information inside the lane. The paper is facing and evaluating two methods to classify this additional lane information. Therefore the images from five cameras mounted around the car are used. Four of them with fisheye lenses. The methods have in common, that the input images are transformed into a bird view projection. First introduced method is to extract contours from the transformed images and collect geometrical features and Fourier coefficients. The second introduced way, is to calculate histograms of oriented gradients and use it as input for the classification step. Both classification approaches are implemented and evaluated as multiclass and single class detectors for each arrow type. Furthermore, the classification results from a support vector machine and random forest were faced for this classification problem. The results from the multiclass detectors are evaluated and presented in form of confusion matrices. With the introduced approaches a high detection confidence could be achieved, proofed with validation datasets and in practical use.

Publication Year 2018
Result 21.

Title Real-Time Global Localization of Robotic Cars in Lane Level via *Lane Marking* Detection and Shape Registration.

Source IEEE Transactions on Intelligent Transportation Systems. 2016/4. 17(4) pp 1039-1050 (Figs., Refs., Tabs.)

URL [http://dx.doi.org/10.1109/TITS.2015.2492019](http://dx.doi.org/10.1109/TITS.2015.2492019)

Abstract In this paper, the authors propose an accurate and real-time positioning method for robotic cars in urban environments. The proposed method uses a robust *lane marking* detection algorithm, as well as an efficient shape registration algorithm between the detected *lane markings* and a GPS-based road shape prior, to improve the robustness and accuracy of the global localization of a robotic car. The authors show that, by formulating the positioning problem in a relative sense, the authors can estimate the global localization of a car in real time and bound its absolute error in the centimeter level by a cross-validation scheme. The cross-validation scheme integrates the vision-based *lane marking* detection with the shape registration, and it improves the accuracy and robustness of the overall localization system. The GPS localization can be refined by using *lane marking* detection when the GPS suffers from frequent satellite signal masking or blockage, whereas *lane marking* detection is validated and completed by the GPS-based road shape prior when it does not work well in adverse weather conditions or with poor lane signatures. The authors extensively evaluate the proposed method with a single forward-looking camera mounted on an *autonomous vehicle* that travels at 60 km/h through several urban street scenes.

Publication Year 2016

Result 25.

Title Reading the Road: *Road Marking* Classification and Interpretation.

Source IEEE Transactions on Intelligent Transportation Systems. 2015/8. 16(4) pp 2072-2081 (Figs., Tabs.)

URL [http://dx.doi.org/10.1109/TITS.2015.2393715](http://dx.doi.org/10.1109/TITS.2015.2393715)

Abstract *Road markings* embody the rules of the road whilst capturing the upcoming road layout. These rules are diligently studied and applied to driving situations by human drivers who have read Highway Traffic driving manuals (*road marking* interpretation). An *autonomous vehicle* must however be taught to read the road, as a human might. This paper addresses the problem of automatically reading the rules encoded in *road markings*, by classifying them into seven distinct classes: single boundary, double boundary, separator, zig-zag, intersection, boxed junction and special lane. The authors' method employs a unique set of geometric feature functions within a probabilistic RUSBoost and Conditional Random Field (CRF) classification framework. This allows us to jointly classify extracted *road markings*. Furthermore, the authors infer the semantics of road scenes (pedestrian approaches and no drive regions) based on marking classification results. Finally, their algorithms are evaluated on a large real-life ground truth annotated dataset from their vehicle.
Abstract

After the January 2019 NCUTCD meeting where the FHWA confirmed that they are working on a new MUTCD, the NCUTCD CAV Task Force engaged the Auto Alliance to obtain information that could be used to generate discussion and direction concerning the need of traffic control devices to support the deployment of automated driving systems (ADS). The strategy employed was to share the news of an upcoming revision of the MUTCD along with the strawman proposal that was developed by the Markings Technical committee’s ADS-RFI Task Force. The strawman proposal includes preliminary suggestions that address pavement marking uniformity issues thought to be helpful to both machine vision systems that provide partial-to-full automation as well as human led vehicles. The specific request was broader than just pavement markings. The anonymized results of the effort are described in this document.

The Auto Alliance (Alliance of Automobile Manufacturers) is the leading advocacy group for the auto industry, represents 70% of all car and light truck sales in the United States, including the BMW Group, Fiat Chrysler Automobiles, Ford Motor Company, General Motors Company, Jaguar Land Rover, Mazda, Mercedes-Benz USA, Mitsubishi Motors, Porsche, Toyota, Volkswagen Group of America and Volvo Car USA.
Disclaimers

• The comments included in this document are ‘raw’ and taken from the feedback. In some cases, there is room for interpretation and follow up. The comments have only been anonymized and categorized for ease of use.

• This is a working draft of suggested TCD practices made by the auto industry to support the deployment of ADS. This material has been developed by the CAV Task Force of the NCUTCD to provide material that can be used to focus discussions and direction within the NCUTCD technical committees. This document does not represent a formal NCUTCD proposal for MUTCD changes. Furthermore, the material presented herein do not represent NCUTCD proposed recommendations for changes to the MUTCD, nor does the material represent an official proposed revision of the MUTCD.
Initial Request

Addressing Cooperative Automated Transportation (CAT) in the Manual on Uniform Control Devices (MUTCD)

The FHWA has announced efforts to update the MUTCD. The National Committee on Uniform Traffic Control Devices (NCUTCD) is working to identify traffic control device (TCD)-related information that can be used to update the MUTCD that support CAT while meeting the needs of current road users.

Background:

Traditional OEMs and new entries in the vehicle industry are introducing new technology in vehicles today. With this in mind, FHWA is preparing to support these new technologies today and in the future through the MUTCD. These initial technologies (lane departure warning, lane keep assist, and sign recognition for example) are the first steps toward full deployment of CAT.

Interoperability is a critical piece of the successful deployment of CAT. This will ensure that vehicles will be able to operate with the same level of safety, comfort and convenience in all areas. To support interoperability, TCD uniformity will be an important component of CAT. Widespread compliance with the MUTCD will improve uniformity and help ensure the successful introduction of a variety of levels of automation in a mixed fleet for the foreseeable future. The mixed fleet will continue to have manually operated vehicles driven by humans. Widespread uniformity of the MUTCD will also benefit human drivers as well as low, mid and high levels of CAT.

There continues to be a great deal of research being conducted on many aspects of CAT. Sensor technology, processing power and development of vehicle control continue to improve. Therefore, the following recommendations are the first steps in addressing CAT in the MUTCD. Future updates to the MUTCD can address new technology and findings from TCD-related research regarding CAT.

Recommendations:

As a foundation or initial step to support the deployment of vehicles with known aspects of CAT today and higher levels of CAT in the future, the NCUTCD CAV Task Force is focused on an initial effort aimed at increasing the uniformity of specific TCD practices. The following aspects of pavement markings are addressed in the current MUTCD but allow flexibility. To increase National uniformity, the NCUTCD CAV Task Force is considering developing MUTCD recommendations focused on the following areas.

- Pavement marking width - developing uniform width of longitudinal markings
- Skip line / gap dimensions - establishing uniform dimensions for skip line length and gap spacing
- Dotted edge line extensions - use of dotted edge line extensions along ramps
- Hatched markings inside gore areas - use of hatching (Chevron markings) inside gores
- Contrast markings used on concrete roadways

Request:

Your feedback is requested on the current focus areas, as well as other high priority areas that the NCUTCD CAV Task Force should be evaluating. Specifically, from your perspective, are the bulleted items expected to be beneficial for machine vision systems (please describe)? Are there other pavement marking uniformity issues that should be considered beyond pavement markings, are there other areas within the TCD space that would benefit machine vision systems with increased uniformity? Finally, from your perspective, please suggest/describe other TCD-related areas that should be considered to support the development of CAT in the MUTCD (i.e., beyond uniform applications of TCDs).

Please respond to the Task Force chair: Paul Carlson, pcarlson@roadinfrastructureinc.com The MUTCD is available on-line at: https://mutcd.fhwa.dot.gov
1. Direct Input on Bulleted Items from Initial Request

1.1. Pavement marking width – developing uniform width of longitudinal markings
   • Yes, this would be particularly beneficial for machine vision.
   • Not sure about a specific dimension but thin markings are problematic and should be avoided.

1.2. Skip line / gap dimensions – establishing uniform dimensions for skip line length and gap spacing
   • Not an issue for us
   • Yes, this is particularly beneficial for machine vision.

1.3. Dotted edge line extensions – use of dotted edge line extensions along ramps
   • These would be very useful and we would love to see them implemented more consistently
   • Yes, this is particularly beneficial for machine vision. It would help for roundabouts too.
   • Also include dashed lines across entrances of turn lanes and lane splits
   • Require dashed intersection turn lines for irregular geometries or long intersections, and for dual turn lanes

1.4. Hatched markings inside gore areas – use of hatching (Chevron markings) inside gores
   • We prefer to not have chevron markings inside of gore areas. In some circumstances these chevron patterns could be erroneously detected as lane markings.
   • Standardizing the hatched marks inside gore areas (right now, adding the hatched markings is optional so you end up with a mixture of some gore areas hatched and others not)

1.5. Contrast markings on concrete roadways
   • On concrete roads mandate adding both the white and black colors to increase contrast
Add dashed lane lines across entrance ramp and exit ramp openings in all states. Some states do this today.
TCD suggestions for ADS

Maintain dashed center lines through intersections without traffic controls (stop lights/signs)

Dashed lines across entrances of turn lanes

Dashed lane line across lane add entrances
Dashed line across lane split following higher ADT roadway.

On concrete roads mandate adding both the white and black colors to increase contrast.
TCD suggestions for ADS

2. MUTCD Part 2 and 7 – Traffic Signs (including School Areas)

2.1. General
- Standardize all traffic signs throughout the entire country.
- Use mainly pictograms, limit use of text. In situations where text is necessary: The content of the text shall be standardized
- Do not allow unique state specific traffic signs.
- All road signage should have good retroreflective background.

2.2. Electronic Signs
   Electronic Signs need to be standardized with reference to:
   - Color – White background color with black text. This background should be retroreflective or illuminated.
   - Shape – All electronic signs should be rectangular in shape and have the same dimensions (standard length and width).
   - The entire sign should be illuminated.
   - The illuminated portion 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. If the refresh rate is known and is standard for all electronic signs, then they will be much easier to correctly detect.
   - Position – The height of all electronic signs should be standardized and not exceed 17 feet in height as measured from the ground to the bottom of the sign.

2.3. Speed Limit Signs
- The speed limit sign should be clearly associated to its specific lane/road. For example in the case of parallel roads with different speed limits.

2.4. School Signs
   School speed limit signs need to be standardized with reference to:
   - Design – All school speed limit 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 shall be standardized.
   - Shape – All school speed limit signs should be rectangular in shape and have the same dimensions (standard length and width).
   - Position – The height of all school speed limit signs should be standardized and not exceed 17 feet in height as measured from the ground to the bottom of the sign.
   - 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. If the refresh rate is known and is standard for all electronic signs, then they will be much easier to correctly detect.
2.5. End school zone

   End school zone signs need to be standardized with reference to:
   - Design – 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 rectangular in shape and have the same dimensions (standard length and width).
   - Position – The height of all end school zone signs should be standardized and not exceed 17 feet in height as measured from the ground to the bottom of the sign.

2.6. Future signs

   - We like the 3M concept of placing infrared-readable bar code type markings on signs for reliable machine-reading, but recognize this may take longer to implement.

2.7. Other sign topics

   - Road signs for “No Turn on Red” and Speed limits (e.g., multiple speed limits on one sign for night/day/truck/minimum speed).
   - Lighted signs for time-of-day-dependent lane directionality (e.g., a center lane that changes travel directions based on morning/evening commute. Some cities use green/red arrows, some use green/red circles in over-lane lighted signs)
   - Many states have additional road signs which are not included in the MUTCD. For example, we have noticed that the State of California implements road signs for speed zone ahead (R2-4(CA)) or ending of a certain speed limit (R3 (CA)) 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 R1-5 / R1-6 Yield Here to Pedestrian signage, ensure there is a stop line or yield demarcation accompanied with it
   - Requirements for reporting temporary or moved traffic control signs (e.g, stop sign, temp traffic signal) ; or a new sign or message easily perceived by AVs to recognize such
3. MUTCD Part 3 – Pavement Markings

3.1. Painted lane-boundaries with good contrast

Perception of lane markings depends on high level of contrast difference between the lane marking and the road surface. Lane markings painted on a bright road surface such as concrete shall be enhanced by additional contrasting colored markings such as black markings left and right of the main lane mark.

Yellow lane markings marking the left edge of the drivable road shall be enhanced as well by supporting the bright yellow color with black markings left and right to the main marking.

![Figure 1: lane markings supported by additional markings of a different color](image)

3.2. Reflectivity

Omni-directional reflectivity of lane lines to ensure directional sun doesn't wash out lines

Mandatory restriping at some % of fade

It would be helpful to have highly reflective pavement markings for driving at night and in the rain (e.g., new markings in CA).

3.3. Edge Lines versus Curbs

Many roads use curb as an indicator of the right hand side of the lane. Curbs and other features have lower contrast than a white lane line. If a center line is present, always include an edge line.
3.4. Non-dedicated exit lanes

Non-dedicated exit lanes leave areas with uncertainty where there is no sufficient guidance available. These areas shall be avoided by adding specific dashed lines along an exit scenario to drag traffic towards the main suggested path.

Figure 2: non dedicated scenarios added with dashed lane markings for additional guidance
3.5. Emergency areas/shoulders
All freeways shall be equipped with emergency areas/shoulders on the side of the lanes. Even dedicated lanes (Special lanes like HOV) which are separated from the main lanes of the freeway should have access to emergency areas.

3.6. Botts dots
Botts dots shall be supported by a painted line below for better visibility by computer vision. The Botts dot itself should also be colored in a way that enhances its visibility in all weather or lighting scenarios.
- Shall be avoided in general
- If required Only together with lane markings/dashed lane
- Lane markings which provide acoustic feedback are generally preferred

3.7. Short dashed lane markings indicating exit only lanes
Short dashed lane markings shall be standardized in terms of
- Marking length (> 3ft)
- Marking width (> 10in)
- Distance between individual markings (> 5ft)

Between the individual marks of a high frequency lane shall be no other markings and/or other obstacles.

3.8. HOV/Express lanes
Dedicated separated lanes such as carpool or express lanes shall be separated from the main flow of traffic in a standardized and uniform way including:
- Separation to the main flow of traffic by a special type of lane markings (for example 2 or 3 solid white lane markings)
- Yellow lane markings for left road edge of separated lane
- Uniform entrance and exit scenarios including dashed lane markings
3.9. Hatched areas

In an exit scenario an open free space is created after the two separating lanes diverge from each other. This free space shall be marked as a non-drivable area of some sort. It is suggested to mark these areas by crossing lines in sort of a grid or hatch pattern. (See left)

Other non-drivable areas such as gore exit areas or areas in front of poles or barriers caused by the free space created by an exit may be specially marked as well.

![Figure 3: Hatched area after an exit scenario](image)

3.10. Other Pavement Marking Items

- Car pool lane boundaries need to be more uniformly marked, including non-traversable areas and traversable (enter/exit) boundaries.
- Bike lane demarcations need to be more uniform
- Multi-line spacing for special use lanes (i.e., double yellow, car pool); it may be covered already in MUTCD but we have seen some non-conformity.
- Contrast markings (i.e., black/white lines used on concrete surfaces). Some States use longitudinal black/white, while others use lateral black/white/black. Pick one.
- Robust paint markings on the road that would help CAT (without an onboard map)
- Large freespace areas, such as large intersections and toll areas, need to be marked better.
- Lane endings and lane splits on highways. Paint more arrows on the particular lane that ends or splits to indicate which way the vehicle should go to stay on the main highway.
- Speed bump notifications (i.e., color of paint on the speed bump, chevrons leading to the speed bump).
4. MUTCD Part 4 – Traffic Signals

- More uniformity in traffic signals (incl. more uniform placement) would be helpful. Particularly problematical are horizontal traffic signals.
- Traffic light illumination requirements (including requirements for vision - seeing variable speed limits (and other types of ITS interactions, like V2I)
- Traffic lights should be standardized for the entire country including: Position, location, color, shape, refresh rate (greater than 200 Hz).
- The shape of traffic lights should be in the shape of light strips, either vertical or horizontal. There should not be block-shaped, T-shaped, or L-shaped traffic lights.
- The traffic lights should have a clear, unambiguous association with the specific lanes.
- Retroreflectivity guidance (e.g., is too much on certain signal backplates bad for AVs?)
- Have strict flickering cycle, color, intensity range; Don't have programable visibility using optical device (mechanical is ok); Light for different vehicle are not too close to each other to avoid confusion (no bike/muni light touching car light); They are positioned on polls in a way that facilitate lane light associations; Any intersection type change (stop to light) or light change is advertise in advance; Timecards have to be in electronic forms; On high speed road/ highway bulbs of different shape should not be showing on same lights.
- Frequency of LED bulbs in traffic signals. Is it standard?

5. MUTCD Part 6 – Temporary Traffic Control

- All construction sites should have traffic signs that warns 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 e.g. orange temporarily lines that remain at their place on the road for a long time 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.
- If the lanes become narrow, that has to be displayed in advance.
- 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.
- 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.
- Construction zone cone spacing (max spacing req)
6. **Other Areas**

6.1. **Pylons**
- Thin vertical poles are challenging to be detected in some situations by computer vision. For these reasons poles shall only be used in combination with proper lane marking for traffic guidance.
- Poles shall always be equipped with high reflective material in order to be better seen.

6.2. **Barriers**
- Concrete walls such as dividers should be marked with highly reflective markers, especially in the beginning section to enhance the visibility.
- The barrier and road separation should be clearly differentiated (good contrast between the barrier and road).
- Steel-rope-barriers are less visible than steel-beam-barriers by computer vision. Steel-beam-barriers or concrete walls with clear reflective markings are preferred.
- Beacons/cones 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.

7. **General Comments**
- The MUTCD as a standard shall be the used consistently throughout all states.
- Centralized database:
  - Centralized database for construction sites, road incidents, road closures, natural disasters affecting roadways.
  - Database with road signs and sign location (latitude and longitude) at least for new signs.
  - Reporting / database for real-time functional signal, traffic control changes or new striping
  - Car accident sites on the roads should not be marked just by police signal lights (the small flare like signal lights on the road) but by bigger Standardized lights that have better visibility to computer vision making assistance of piloted cars to stop ahead on time.
  - Special markers indicating the lane number to enable lane level positioning.
- We support this update effort. In addition to the update to MUTCD, we also see the need for more enforcement of existing MUTCD guidelines and any future updates. Compliance is needed to make CAT and human-driving easier.
- States implement road signs which are covered by the MUTCD but don’t always fully follow its recommendation. At minimum, such differences should be notified to the public, when adopted. FHWA and the NCUTCD should collaboratively develop a process to develop an all new Appendix to the MUTCD which summarizes unique requirements from each States. For example, if and when a State adopts a road sign (or any other TCD) which are different from the recommendations of the MUTCD, FHWA could request a State to report such information to FHWA and the NCUTCD. FHWA and NCUTCD could then use this information to update the unique requirement summary database. The centralization of TCD information across the nation would be beneficial for the industry in accelerating the ADS development.
- Rail crossings - white lines for dynamic envelope & all new rail crossings must be signalized