NCHRP Project 20-113F

Preparing for Automated Vehicles and Shared Mobility: State-of-the-Research Topical Paper #3

INFRASTRUCTURE ENABLERS FOR AUTOMATED VEHICLES AND SHARED MOBILITY

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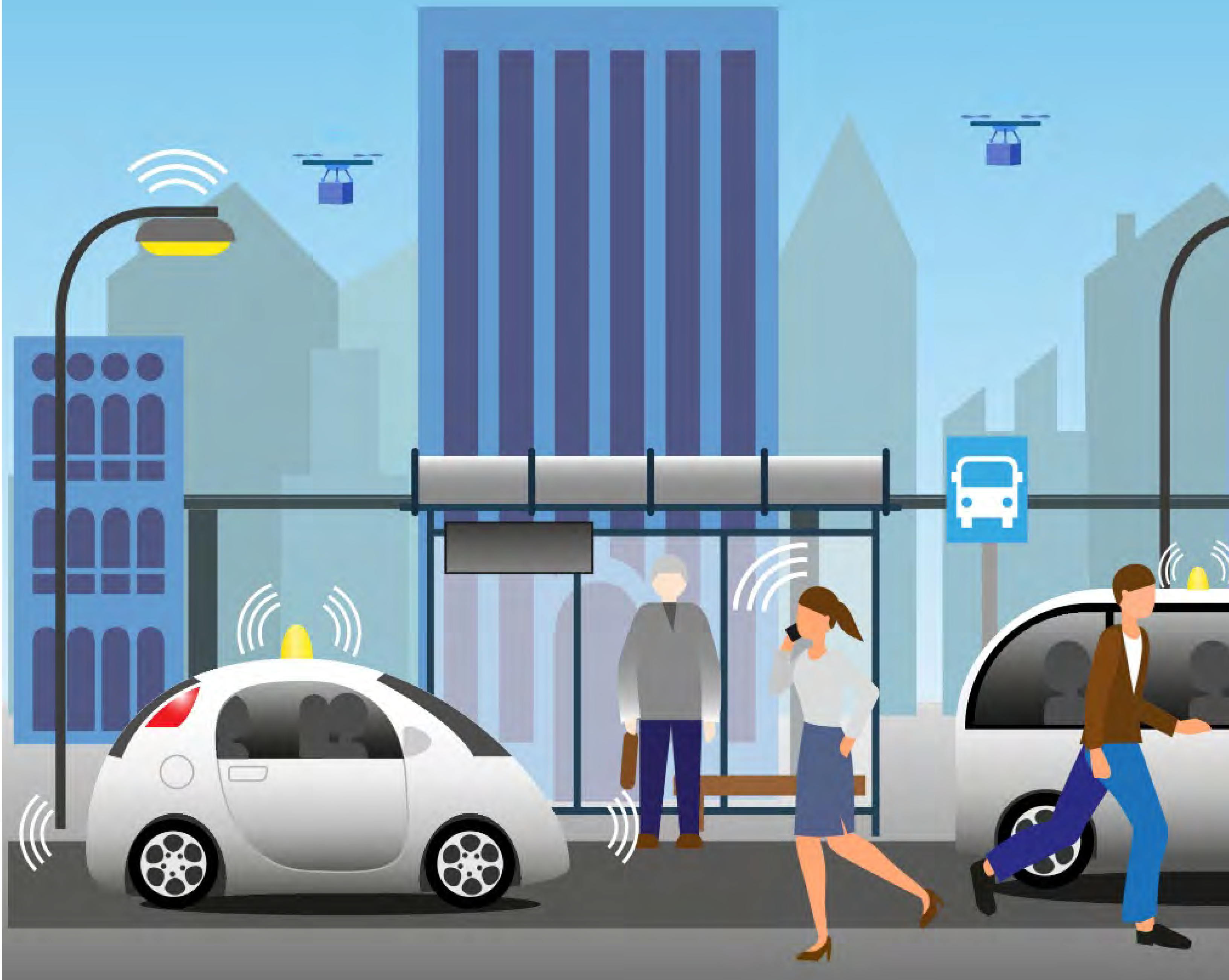
TRB AV/SM FORUM
AUTOMATED VEHICLES + SHARED MOBILITY

1 Introduction

1.1. Background

In coordination with the National Cooperative Highway Research Program (NCHRP), the TRB Forum on Preparing for Automated Vehicles and Shared Mobility (Forum) has developed nine (9) Topical Papers to support the work of the Forum (Project).

The mission of the Forum is to bring together public, private, and research organizations to share perspectives on critical issues for deploying AVs and shared mobility. This includes discussing, identifying, and facilitating fact-based research needed to deploy these mobility focused innovations and inform policy to meet long-term goals, including increasing safety, reducing congestion, enhancing accessibility, increasing environmental and energy sustainability, and supporting economic development and equity.



The Topical Areas covered as part of the Project include the following:

- Models for Data Sharing and Governance
- Safety Scenarios and Engagement during Transition to Highly Automated Vehicles
- Infrastructure Enablers for Automated Vehicles and Shared Mobility
- Maximizing Positive Social Impacts of Automated Vehicle Deployment and Shared Mobility
- Prioritizing Equity, Accessibility and Inclusion Around the Deployment of Automated Vehicles
- Potential Impacts of Highly Automated Vehicles and Shared Mobility on the Movement of Goods and People
- Impacts of Automated Vehicles and Shared Mobility on Transit and Partnership Opportunities
- Implications for Transportation Planning and Modeling
- Impacts and Opportunities Around Land Use and Automated Vehicles and Shared Mobility

For this Project, the important goals of the papers are to provide a snapshot of all research completed to date for a Topical Area and within the proposed focus areas identified below. The papers are intended to provide a high-level overview of the existing research and to make recommendations for further research within a Topical Area. The Project establishes a foundation to guide the use of resources for further development and support of more comprehensive research that tracks the identified research gaps noted in each Topical Paper and to support the Forum.

The research reviewed varies by paper, but generally, only published research was included as part of the Project. For clarity, the scope of the project is to report on research that has been done without judging or peer reviewing the research conducted to date and referenced herein. While considered for background purposes, articles, blog posts, or press releases were not a focus for the work cited in the Topical Papers. Also, in consideration of the focus of the Forum and the parameters of the Project, the research was narrowed to publications focused on the intersection between automated vehicles and shared mobility. Materials reviewed and cited also include federal policy guidance and applicable statutes and regulations.

Each of the papers is written to stand on its own while recognizing there are cross over issues between the Topical Areas. If desired, readers are encouraged to review all nine Topical Papers for a more comprehensive view of the Project and the points where topics merge.

The goals of the Topical Papers are the following:

Snapshot of research completed under a particular topic area

Summary of research completed to date

Identification of gaps in research

Recommendations for additional research

1.2. Approach to Topical Paper Development

The approach to development of the Topical Papers and their focus included the following:

- Meetings with the Chairs of the Forum
- Engagement with the Members of the Forum, including during the Forum meetings in February and August of 2020
- Feedback from Chairs and Forum Members during the development of focus areas for the Topical Papers and receiving comments to the draft versions of the papers

During the meetings with the Forum in February 2020, the research team discussed the Project with the Forum over two days in two separate sessions. On Day 1, the research team presented the proposed scope for each Topical Paper and broke out into groups to further refine the focus of each paper to match the interest and goals of the Forum and its Members. During Day 1, the Forum also heard from different organizations highlighting previous and ongoing research. These organizations[1] included the following:

- Brookings Institution
- The Eno Center for Transportation
- National Governors Association
- Future of Privacy Forum
- AARP
- American Public Transportation Association

On Day 2, the research team reconvened with the Forum to summarize the break-out discussions on Day 1 and to receive final comments on the focus for each Topical Paper.

In August 2020, the draft papers were presented to the Forum for review and feedback. Comments were received in writing and verbally during a virtual Forum meeting. The final papers incorporate the comments and feedback received as part of the review process. This paper identifies a large body of research regarding this topic area associated with shared and automated vehicles. As reviewer comments pointed out, there remains considerable uncertainty regarding if and when highly automated vehicles will be deployed on a large scale. This is reflected in much of the research that has been completed to date. Consequently, this paper summarizes common themes from the research available to date as much as possible, while acknowledging that various scenarios may impact the issues, recommendations, and areas for future research. Many of the issues addressed in this research are forward-looking and anticipate an environment where fully automated vehicles (SAE Level 5) are a ubiquitous part of the transportation system.

[1] The research team and the Forum thank these organizations for their time in sharing their work and insights in support of the development of the Topical Papers.

2 Paper Areas of Focus

This Topical Paper reviews research conducted and published as of July 10, 2020. In approaching this topic, the paper focuses on the following issue areas:

1. Critical elements of infrastructure, including vehicle to infrastructure (V2I) communications, markings and striping, signage, intelligent transportation systems (ITS), pavement condition, and other smart or embedded infrastructure components
2. Consideration of market penetration 'tipping points' for enabled vehicles that causes agencies to invest in the necessary roadside and deskside hardware
3. Potential upgrades to transportation infrastructure, such as embedded sensors, cameras, bike stations, electronic tolls, adaptive traffic signals, etc., that can enhance the travel experience and the effect of infrastructure on supply and demand for transportation services
4. Influence of infrastructure on promotion of new mobility innovation, including electric vehicles, demand responsive platforms, and shared mobility; at what point is there enough market penetration to justify infrastructure investments
5. Issues associated with 5.9GHz spectrum allocation and impacts on safety
6. The role governance has when considering infrastructure issues, including defining spaces in communities and right of way management

For ease of use, this Topical Paper does make an attempt to keep these individual topics clustered, however, in some cases the underlying research findings may be limited to specific applications or activities.

3 Summary of Findings

AVs, including connected AVs, are increasingly being used on U.S. public roadways for both passenger and goods movement. Recognizing this, state and local departments of transportation (DOTs) are interested in understanding what elements of highway infrastructure to prioritize, while balancing budget constraints and limited personnel resources with the desire to facilitate AV use and adoption. While there remains substantive debate over the need for infrastructure to enable automation, there is little disagreement that these technologies will influence design, maintenance, planning, and operations of the publicly controlled – and in some instances – privately operated infrastructure. For example, some changes and enhancements to the current road infrastructure may be required to facilitate the seamless, safe adoption of AVs incorporating machine vision principles. Governments interested in having HAVs on their roads need to plan for and invest in such changes.

This Topical Paper provides a summary of the state of the practice concerning research on infrastructure enablers and practices as they relate to shared mobility and automated vehicles. Through reviewing the body of literature on infrastructure considerations to accommodate HAVs within the context of the areas of focus noted above, several common themes emerge:

- **Understandably, the current infrastructure is designed for human drivers**. Existing standards are based on the idea that human performance has limitations. Lane widths, speeds, curve ratios, and following distance determine design standards and operational decision making. At lower vehicle automation levels (SAE Levels 1 and 2), vehicles are expected to use existing road infrastructure and follow design practices. At higher levels (SAE 3+), technology is available to assist in moving towards HAVs with human drivers either partially or completely unengaged in the driving task, or even with no driver at all. Therefore, adaptation of current infrastructure requires additional consideration. Enabling AVs to travel along public roads may require independent lanes, different infrastructure upgrades or adjustments under different future scenarios, and potentially new materials or methods.

- **Many research efforts in the infrastructure space address a number of overlapping topics**. For the most part, the research does not focus on a particular infrastructure element, but rather a combination of general infrastructure enablers and impacts. For example:
    - Many research initiatives look at machine vision as it relates to interpreting pavement markings and interpreting signs.
    - Investigations of the impacts on pavements and structures often include discussion on embedded sensors and smart pavements.
    - Discussions of electrification often combine the advancement of electrification and shared platforms and charging equipment.
    - The reports on communications technologies such as dedicated short-range communications (DSRC) are often part of broader discussion of ITS, not only as DSRC related to HAVs.
    - Examinations of communications spectrum issues often include safety-focused infrastructure development and design.

- **Lane markings, traffic signals, and road signs should be readable for AVs.** HAVs and shared mobility options will exist in mixed fleet environments for decades. As such, markings, signals, and signs must remain as critical elements in advancing new technologies.

- **Vehicle to infrastructure technology and digital infrastructure associated with enabling vehicle-based communications will play an important role in the future and will require some government investments.** Debate remains about the industry's reliance on government-supported and supplied traveler information, but much research has described a renewed emphasis on the digital infrastructure requirements of emerging technologies. This includes protection of the dedicated spectrum needed for communications and high definition mapping requirements for navigation.

- **Long-term impacts of AVs and shared mobility on the physical infrastructure remain unknown.** The performance of pavements, bridges, and other physical assets following a transition to highly automated travel is largely unstudied and highly uncertain. Changes in vehicle following distances, lane positioning, acceleration, and other practices can alter the expected performance of built infrastructure. Changes to freight movements, including platooning, could also impact pavement and structural conditions.

- **Increased investment in traveler assistance services, including mounted variable messaging, 511 systems, and traffic management, may be unnecessary or redundant over time.** Many governmental investments in data collection and real-time monitoring have been delayed or greatly reduced in the past several years as new mobile technologies and hand-held devices gained market share and acceptance. A similar decreased reliance on ITS and traveler assistance services could be a foreseeable outcome emerging from new vehicle and platform designs.

- **Among the areas where research has shown the largest impacts are: setting regulatory policy, encouraging pilot developments, identifying work zones, and data frameworks.** These "foundational" research areas provide substantial evidence of the need for additional research bridging the gap between public and private sector motivations and roles for further development of emerging technologies. The recommendations of private firms developing new technologies and the emerging policies and frameworks, while not incongruous, do include some gaps in expectations.

- **Different end uses and vehicle types would require varying infrastructure enablers.** A low speed shuttle can likely operate without sign recognition, with or without dedicated lanes, and with minimal infrastructure modifications. High speed, intercity travel has different requirements, as would complicated urban environments. Truck platoons and automated commercial vehicles could have even different needs for lane widths, pavement selection, and advanced traveler information.

- **Several discussion trends**[2] **have also been identified concerning the growth and testing of highly automated systems and vehicles and their overall impacts on the built environment.** These trends include:

    - The varying influences of market penetration, fleet characteristics, and consumer acceptance.
    - Potential land use and parking impacts.

[2] Suganuma, N.: Trends in development of autonomous vehicles and challenges for deployment in society. IATSS Research. 43(4): 242-243 (2019).

- o Different infrastructure needs for alternative power technologies and drivetrains for both passenger and freight vehicles.
- o Other influences (not limited to cost concerns, safety influences, and technology limitations).

There remains great debate on what responsibility infrastructure plays in the development and advancement of automated technologies and shared mobility options.[3] Some argue that infrastructure needs are a substantial component required to accelerate the progress and adoption of these technologies. [4] These needs can include a host of requirements from pavement markings and curb modifications to support facilities and dedicated lanes Other researchers posit that consumers feel AVs will lead to safety degradations, privacy and security risks, and even travel inefficiencies.[5] Others portend that, in order to be ubiquitous, vehicles need no specific infrastructure since they would need to operate on all types and styles and classifications. Further research contends that the vehicles should include required redundancy in sensing principles for vehicle lateral position to make vehicle automation safe, regardless of the infrastructure clues. This position requires accepting shared responsibility for enabling automated technology.[6] This Topical Paper builds upon many questions and developments, including past work targeting primary drivers for expanding use of AV systems.[7]

Addressing these discussion trends will be the impetus for additional research and outreach by the Forum and others. The great deal of uncertainty surrounding the development and ultimate implementation of these new technologies provides strong challenges for transportation leaders. This uncertainty has led to a number of conflicting research opinions, findings, and results from works in progress. The great variation evident from the market penetration projections is perhaps the largest influence on infrastructure enabling. Finding answers on appropriate levels of public sector investment in infrastructure in this uncertain environment remains an area yet to be explored. What do we do when we have 5%, 25%, or 50% AV use? Bittner and others attempted to address this question in long range planning efforts in Missouri[8], and other experts have presented ranges of governmental needs.

4 Summary of Research Reviewed

Our research effort included review of papers and reports developed by individual university transportation centers in the United States, FHWA studies, published papers in academic journals, state sponsored initiatives, corporate research and development work, and NCHRP-sponsored research. This variety of research points to a wide range of opinions on the value of

[3] Litman, Todd. Autonomous Vehicle Implementation Predictions Implications for Transport Planning. Victoria Transportation Policy Institute. June 2020.
[4] Duvall, Tyler; Hannon, Eric; Katseff, Jared; Safran, Ben; and Tyler Wallace: A new look at autonomous-vehicle infrastructure. McKinsey, May 22, 2019.
[5] Acheampong, R. A., and Cugurullo, F., 2019. Capturing the behavioural determinants behind the adoption of autonomous vehicles: Conceptual frameworks and measurement models to predict public transport, sharing and ownership trends of self-driving cars. Transportation Research Part F, 62, 349-375.
[6] Radar based pavement markings (concept) see: http://www.diva-portal.org/smash/get/diva2:1132434/FULLTEXT02.pdf
[7] "Driverless Vehicles: What Should Be at the Top of Our List?" Arizona State University Center for Science, Policy & Outcomes, 2019. https://cspo.org/wp-content/uploads/2019/01/Issue-Advisory-Driverless-Vehicles.pdf
[8] Missouri DOT Long Range Transportation Plan update 2019

infrastructure components for enabling advances in automated vehicle technology. While there is much research on the social and economic[9] impacts of automated driving, there is more limited discussion on the key infrastructure pieces.

Many researchers have noted this limited ongoing research discussion on specific infrastructure requirements for automated driving.[10][11][12][13] Original equipment manufacturers (OEMs) have indicated a need for good markings, clear pavements in winter conditions, and well maintained roadways generally. The integration of high-level AVs on the current road network is expected to have impacts on traffic efficiency and safety. At the same time, it does also require the upgrades or adjustments of current road infrastructure[14]. The adjustments typically follow key needs for pavement markings, general ride conditions, and abundant space for lane detection. Other researchers have focused on the elements of market-based approaches to determine infrastructure needs. The goal of this research is to better understand AV adoption decisions and duration to adoption decisions.[15]

In the United States, the Manual for Uniform Traffic Control Devices (MUTCD) defines the standards used by road managers nationwide to install and maintain traffic control devices on all public streets, highways, bikeways, and private roads open to public travel. The MUTCD is published by the Federal Highway Administration (FHWA). FHWA has efforts underway to support advanced driver assistance systems (ADAS) technologies, such as lane departure warning, lane keep assist, and sign recognition that are being woven into MUTCD standards through the National Committee on Uniform Traffic Control Devices, which recommends changes to FHWA. The National Committee on Uniform Traffic Control Devices established a working group to explore further changes to recommendations on signage and lane markings for AVs. The research presented in this section would need to ultimately be built into the MUTCD.

This section follows the structure of the February 2020 Forum meeting to identify research and emerging issues in seven topic areas: infrastructure elements, market penetration, infrastructure upgrades, new mobility innovations, governance, digital infrastructure and safety, and infrastructure features requiring adaptation.

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[9] Johnsen, Annika & Strand, Niklas & Andersson, Jan & Patten, Christopher & Kraetsch, Clemens & Takman, Johanna. (2017). Literature review on the acceptance and road safety, ethical, legal, social and economic implications of automated vehicles.

[10] Nitsche, I. Mocanu and M. Reinthaler, "Requirements on tomorrow's road infrastructure for highly automated driving," 2014 International Conference on Connected Vehicles and Expo (ICCVE), Vienna, 2014, pp. 939-940, doi: 10.1109/ICCVE.2014.7297694.

[11] https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-transport/automated-road-transport/maven

[12] Farah H., Erkens S.M., Alkim T., van Arem B. (2018) Infrastructure for Automated and Connected Driving: State of the Art and Future Research Directions. In: Meyer G., Beiker S. (eds) Road Vehicle Automation 4. Lecture Notes in Mobility. Springer, Cham

[13] Lawson, Steve (2018), Tackling the Transition to Automated Vehicles, Roads that Cars Can Read Report III, European Road Assessment Association (www.eurorap.org); at https://bit.ly/2IrYTTQ.

[14] https://connectedautomateddriving.eu/about-us/cartre/

[15] Asmussen, K.E., A. Mondal, and C.R. Bhat, "A Socio-Technical Model of Autonomous Vehicle Adoption Using Ranked Choice Stated Preference Data," Technical paper, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, July 2020

4.1. Critical elements of infrastructure, including machine vision, markings and striping, signage, ITS, and other smart or embedded infrastructure components

4.1.1 Machine Vision and Issues Associated with Camera Based Sensing

Machine vision capabilities are one of several critical components for development of automated vehicles

Machine vision capabilities are one of several critical components for development of automated vehicles.[16][17] These capabilities are one of many emerging technologies for advancing automation but are likely the most reliant on existing infrastructure components. Nearly all new vehicles on the road are equipped with some form of ADAS including lane departure warning and lane keep systems. Machine vision for ADAS and AVs consists of mounted cameras and image sensors that feed data, in the form of digital images, to the vehicle's image signal processor. The image signal processor then runs complex algorithms on that data and provides input to the vehicle's main computer.[18] Once machine vision can assist a vehicle with identifying and recognizing potential hazards, as well as how to avoid them, automated vehicles will be much closer to widespread deployment.[19]

Color machine vision is critical as the ability to interpret signs and other roadside appurtenances is essential. A team at Northwestern University developed a technique for achieving effective real-time color recognition in outdoor scenes. The technique uses multivariate decision trees for piecewise linear non-parametric function approximation to learn the color of a target object from training samples, and then detects targets by classifying pixels based on the approximated function.[20] Australian researchers found that shape is more important.[21] Other work looks at edge detection[22], corner detection[23], or object classification.[24] Consistency becomes the critical factor in understanding how machine vision will influence the accelerated adoption of automated driving technologies.

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[16] A. Moujahid, M.E. Tantaoui, M.D. Hina, A. Soukane, A. Ortalda, A. ElKhadimi, A. Ramdane-Cherif. Machine learning techniques in ADAS: a review Proc. of 2018 International Conference on Advances in Computing and Communication Engineering (22-23 June 2018), 10.1109/ICACCE.2018.8441758

[17] Harper, C. D., Hendrickson, C. T., Samaras, C. Cost and benefit estimates of partially-automated vehicle collision avoidance technologies. Accident Analysis & Prevention, 95, 104–115. 2016

[18] 3M. Intertraffic.com. Machine Vision and Contrast: How Automated Vehicles See thee Roads. Posted 15 May 2019. https://www.intertraffic.com/news/articles/machine-vision-and-contrast-how-automated-vehicles-see-the-roads/

[19] West, Perry. An Overview of Machine Vision and Autonomous Vehicles. Webinar. Available at https://www.visiononline.org/webinar-detail.cfm/webinars/improving-car-safety-with-machine-vision-a-new-perspective-on-autonomous-vehicles/id/41. 2018

[20] Buluswar, Shashi and Draper, Bruce. Color Machine Vision for autonomous vehicles. Engineering Applications of Artificial Intelligence. Volume 11, Issue 2. April 1998. P 245-256.

[21] Austroads AP-R580-15: Implications of Traffic Sign Recognition Systems for Road Operations. 2018. https://austroads.com.au/publications/connected-and-automated-vehicles/ap-r580-18

[22] Chen Z., Chen Z. (2017) RBNet: A Deep Neural Network for Unified Road and Road Boundary Detection. In: Liu D., Xie S., Li Y., Zhao D., El-Alfy ES. (eds) Neural Information Processing. ICONIP 2017. Lecture Notes in Computer Science, vol 10634. Springer, Cham

[23] T. Wenzel, S. Brueggert and J. Denzler, "Additional traffic sign detection using learned corner representations," 2016 IEEE Intelligent Vehicles Symposium (IV), Gothenburg, 2016, pp. 316-321, doi: 10.1109/IVS.2016.7535404

[24] J. Redmon, S. Divvala, R. Girshick, A. Farhadi You only look once: unified, real-time object detection Proc. of IEEE Conference on Computer Vision and Pattern Recognition (27-30 June 2016), 10.1109/CVPR.2016.91

Machine vision systems look out roughly 20-60 feet, with new developments extending sight distances to 600 feet. There is no difference in terms of the expected machine vision view window sizes or optimums in a day versus night scenario.[25] As expected, retroreflectivity matters for nighttime performance. Several laboratory studies found that omni-directional reflectivity of lane lines ensures directional sun doesn't wash out lines for the machine vision devices.[26] NCHRP 20-102(06) Road Markings For Machine Vision explored the requirements for width, reflectivity, and other needs. The research found that six-inch marking width provides a measurable benefit versus four-inch. This finding is consistent with requests made last year by Google and Tesla to Caltrans that the agency adjust its road markings from a four-inch to a six-inch width. NCHRP 20-102(6) also demonstrated how glare from the sun can wash out otherwise visible markings. The same project has also demonstrated the need to establish metrics to specify, measure, and maintain pavement markings for lane departure warning technologies, specifically daytime performance metrics. This includes, but is not limited to, factors such as daytime luminance to achieve contrast; standardizing contrast patterns on light-colored pavements, again to achieve contrast; and developing ways to assess the washout potential of certain marking materials and applications under glare conditions caused by the sun.

Vision-based systems are evolving with smaller, higher resolution and stereo vision cameras. They prevail where radar sensors fail in object recognition and image classification. Camera sensors are relatively low cost but require high processing power. Good quality images can be obtained under favorable lighting and weather conditions but poor quality otherwise.

Road recognition (defining the lane boundaries and physical characteristics of the travel path) becomes an important infrastructure related enabling technology. Road recognition technology is a difficult area of study. Considering the practical application of the driving environment, researchers have used (light detection and ranging, LiDAR) and radar echo to determine roadway limits. Tests on running vehicles show that the proposed methods of road recognition using LiDAR can work efficiently in real traffic environments.[27]

LiDAR and infrared are emerging technologies for automotive applications. Neither are extensively used due to their high cost. LiDAR sensors provide high resolution 3D imaging which will be critical for autonomous driving. However, like camera sensors, they are sensitive to weather conditions. Infrared sensors on the other hand, provide night vision capabilities. These sensor technologies will need to be more affordable to be attractive for widespread use in vehicles.

4.1.2 Markings

Expanding on the machine vision elements, markings emerged as the primary immediate infrastructure need to enable automated vehicles. Closely related to the machine vision research, research on markings has used both camera and sensor technology.[28] Based on the

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[25] Davies, Chris. Pavement Markings Guiding Autonomous Vehicles. A Real World Study. 2020

[26] A. Geiger, P. Lenz, and R. Urtasun. Are we ready for autonomous driving? the kitti vision benchmark suite. In Computer Vision and Pattern Recognition (CVPR), 2012 IEEE Conference on, pages 3354–3361. IEEE, 2012.

[27] Zhang, Qinzhen and Deng, Weidong. A Method of Road Recognition based on LiDAR echo signal. Lecture Notes in Electrical Engineering, vol. 210, pp. 397–406. 2013.

[28] Visual requirements for human drivers and autonomous vehicles (FHWA) https://www.fhwa.dot.gov/publications/research/ear/16038/16038.pdf

current state of knowledge, pavement markings stand out as one of the most important infrastructure needs for today's partial AVs (SAE Level 2) as well as the more capable AVs of the future (SAE Level 3-5).

If these assets require a system-wide update and higher maintenance standards, what is the best approach to optimize such investments—i.e. how much, and when? Connected automated vehicles (CAVs) mainly depend on their cameras detecting the road markings for the sake of orienting themselves in the middle of a lane and detecting safe stopping points at junctions. Robust lane detection based on markings is therefore essential. For accurate detection, road markings need be clearly visible to cameras and as noted in the 20-102(06) findings, 6-inch markings perform better than 4-inch. Ongoing maintenance, including recurring inspection and re-painting of the road markings, ensures they are identifiable. Faded pavement markings have been continually referenced as a problem for ADS and other camera-based technologies already on the market.

Some weather conditions impact the visibility of road markings, even if they are well-maintained. For example, snow covering roads would obstruct the visibility of the regular markings of these roads. In jurisdictions that receive regular snowfall, consideration should be given to all-season detectable markings. These may include position information that can be retrieved from pavement-embedded sensors and/or Radio-Frequency Identification (RFID) tags. On rainy days, wet roads can create challenges for in-vehicle cameras to successfully identify road markings. Advances in radar-based supplements to machine vision for pavement markings are generally held up to assist in this weather challenge[29]. Approaches to fuse information from non-automated vehicles ahead of the subject automated vehicle provide experiential learning for the onboard systems.[30]

Lane markings and signage should be maintained to a high standard in terms of cleanliness, clarity, non-deterioration, non-ambiguous positioning, and non-obscuration.[31] To design appropriate road markings for automated vehicles, additional discussion is needed as technology advances. MnDOT investigated appropriate pavement marking dimensions and contrast for human vision and driver comfort. The results of this study provide insight as to how MnDOT can effectively leverage its resources to provide pavement markings that effectively meet the needs of all road users. OEMs generally have requested consistent lane marking widths, along with other features as potential infrastructure focused enablers to advance automated technologies.[32]

In March 2019, the American Traffic Safety Services Association adopted policy on road markings for machine vision systems that set preferred standards for inclusion in the MUTCD. The American Traffic Safety Services Association supports road marking and machine vision proposals that will include minimum retroreflectivity standards, 6-inch longitudinal markings, 15-foot-long markings for lanes, dotted exit line extensions, removal of Botts' Dots and contrast striping on concrete roadways.

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[29] A. Gern, U. Franke and P. Levi, "Advanced lane recognition-fusing vision and radar," Proceedings of the IEEE Intelligent Vehicles Symposium 2000 (Cat. No.00TH8511), Dearborn, MI, USA, 2000, pp. 45-51, doi: 10.1109/IVS.2000.898316

[30] A. Gern, R. Moebus and U. Franke, "Vision-based lane recognition under adverse weather conditions using optical flow," Intelligent Vehicle Symposium, 2002. IEEE, Versailles, France, 2002, pp. 652-657 vol.2, doi: 10.1109/IVS.2002.1188025.

[31] Davies, 2020.

[32] National Committee on Uniform Traffic Control Devices Connected-Automated Vehicle (CAV) Task Force. TCD suggestions for Automated Driving Systems (2019).

Additional research on road markings, including weather adaptations, durability, and consistency remain underway. Ultimately, the ability to implement standardization relies on a large number of local units of government. In summation, while road markings remain a relatively low-cost, high impact infrastructure enabler and a critical element for consideration, they do require a lot of investment to complete the network.

4.1.3 Signs

One of the primary findings of sign-based research in the context of automated vehicles is the extreme variation in traffic signs around the world. This means that the problem of consistent, accurate detection and recognition is far from being solved.[33]

Automated vehicles may require special signs.[34] Passive RFID systems have been tested for sign recognition. A benefit of RFID-based approaches is that the same information used to identify the sign in an automated vehicle can support asset management and inventory demands as well[35][36][37]. However, these needs depend substantially on the end use of the automated vehicles. Low speed shuttles can operate on a fixed route or lane detection and do not need sign recognition. Higher speed uses and non-routed applications require some degree of sign recognition. Most AV applications depend on smart vehicles with limited connectivity needs or, especially in the case of higher speed uses, rely on vehicle-to-vehicle communications rather than sign recognition currently. However, this is rapidly changing. Some of the issues raised in the Lawson research included: a need to provide greater standardization of traffic signs throughout the entire country, greater ability to recognize pictograms with limited use of text on signs (in situations where text is necessary, the content of the text shall be standardized), reduced reliance on unique state specific traffic signs, and standardizing good retroreflective backgrounds for traffic signs.

One of the primary findings of sign-based research in the context of automated vehicles is the extreme variation in traffic signs around the world

Automated vehicles can be enabled by a variety of sensors, including radar, sonar, LiDAR, and camera systems. Improved optical character recognition technology is expected to enhance simple shape and legend recognition as research improves.[38] Research shows that sign recognition can be improved by increasing sign size to assure signs exceed minimum pixel size filtering. Larger sign sizes also mean they are detected at a greater distance to allow longer processing and reaction time. Fewer words and the symbol sign equivalent of the text version of

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[33] Traffic Signs in the Evolving World of Autonomous Vehicles. 2019.

[34] Steve Lawson (2018), Tackling the Transition to Automated Vehicles, Roads that Cars Can Read Report III, European Road Assessment Association (www.eurorap.org); at https://bit.ly/2IrYTTQ.

[35] Park S., Lee H. Self-Recognition of Vehicle Position Using UHF Passive RFID Tags. IEEE Trans. Ind. Electron. 2013;60:226–234. doi: 10.1109/TIE.2012.2185018.

[36] Măriuţ F., Foşalău C., Zet C., Petrişor D. Experimental Traffic Sign Detection using I2V Communication; Proceedings of the 35th International Conference on Telecommunications and Signal Processing (TSP); Prague, Czech Republic. 3–4 July 2012; pp. 141–145

[37] Yu Y., Li J., Guan H., Wang C. Automated Extraction of Urban Road Facilities Using Mobile Laser Scanning Data. IEEE Trans. Intell. Transp. Syst. 2015;16:2167–2181. doi: 10.1109/TITS.2015.2399492

[38] https://devpost.com/software/ocr-driven-automated-vehicle#updates

warning signs provides additional value. Improved character recognition is achieved by standardizing font type, size, message, and sign placements, as well as adopting sign maintenance practices to keep signs clean and unobstructed by vegetation or other roadway infrastructure to provide a clean line of sight for cameras.

Autonomous vehicle software was "trained" to read thousands of signs in Mapillary's library of 500-odd sign types from more than 60 countries, using what engineers call "neural networks"—a computer system that "studies" lots of tweaked versions of a thing to learn how to infer what it is, at any angle or condition.[39] This research provided a library to draw upon for other automated systems.

Additional research has also concluded that automated systems can be "tricked" into misinterpreting signs if they include graffiti, incidental damage, or intentional obscuration.[40] Variable message signs can be confusing based on the refresh rates that machine vision technologies can interpret.

Combining the results of sign and marking research, coupled with standardization of key fonts, colors, materials, and distances provides a base for additional implementation and pilot studies.

4.1.4 ITS Devices and Existing Embedded Sensors

For the purposes of this paper, ITS devices include electronics, communications equipment, computers, controls, and sensing and detecting devices throughout the transportation system in order to improve safety, efficiency of service, and traffic modulation through transmitting real-time information.[41] Early discussions of automated vehicle and shared mobility options involved building communications and sensor infrastructure into "smart roads" to assist in the operation of AVs and other vehicles. More modern deployments have relied instead on AVs to have their own sensory abilities and to communicate with other vehicles (V2V).[42] ITS investments appear to have limited effect as a potential infrastructure enabler for shared mobility and AVs. However their uses in connected vehicle programs has been extensively studied through the Connected Vehicle Pilot Program.[43] Tampa Hillsborough Expressway Authority, along with New York City Department of Transportation and the Wyoming DOT, are implementing multiple connected vehicle applications that will help to improve safety, mobility, and reduce environmental impact.

It is generally unknown how well vehicle automation systems will perform, how often faults or system limits will occur, or how predictable machine behavior will be in response to installed ITS equipment, including variable messaging signs, dynamic speed limits, and smart work zones. Current research on these topics is underway through the Institute of Transportation Engineers.[44]

ITS investments that include variable message signs, those enabling 511 systems, and radio-based traffic alerts may be reduced according to said research. Other officials have disputed

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[39] Bliss, Laura. How to Teach a Car a Traffic Sign. Bloomberg CityLab. February 10, 2017.
[40] Eyholt, Kevin, Evtimov, Ian, Fenandes, Earlence, Li, Bo, et al. Robust Physical-World Attacks on Deep Learning Visual Classification. https://arxiv.org/pdf/1707.08945.pdf
[41] USDOT ITS Joint Program Office, ITS Strategic Plan 2020-2025
[42] "Issue Overview: Infrastructure." Autonomous Vehicles Policy Initiative. Tabman Center at Harvard Kennedy School. https://www.hks.harvard.edu/sites/default/files/Taubman/AVPI/Infrastructure%20Basic.pdf
[43] USDOT ITS Joint Program Office, Connected Vehicle Pilot Deployment Program, https://www.its.dot.gov/pilots/index.htm
[44] https://www.ite.org/technical-resources/standards/connected-intersections/

this finding, although we have been unable to find specific reference to ITS infrastructure as a key enabling technology. The connected vehicle programs have provided several lessons learned on ITS and sensor technologies, including failures of roadside units and equipment following lightning strikes.[45]

The connection between ITS devices and AV remains uncertain. Shared mobility uses have benefited from enhanced travel time information, dynamic routing, and other congestion improving options.

4.1.5 Lighting and Traffic Signals

If lighting and signalization are included in the broad definition of ITS, several studies have expanded upon the need for better and more comprehensive roadway lighting and signalized intersection controls. These include design, more visibility, countdown timers, connected technologies, and intelligent lights.[46] Some researchers have identified increased investments in traffic management for corridor operations through improved signal phasing and timing to assist AV operations.

More uniformity in traffic signals (including more uniform placement) may also be helpful. Research has shown that horizontal traffic signals are particularly problematic.[47] Traffic light illumination requirements can be standardized (including requirements for vision – e.g. seeing variable speed limits).[48] Other research shows that traffic signal characteristics could be standardized for the entire country including: position, location, color, shape, and refresh rate (at greater than 200 Hz. vehicles struggle with block-shaped, T-shaped, or L-shaped traffic lights).

Retroreflectivity guidance questions remain (e.g., is too much reflectivity on certain signal backplates bad for AVs?). There are other research questions such as cycle, color, and intensity ranges as well.

With respect to traffic control devices, including signs, markings, and traffic signals, the existing body of research presented above generally provides the following preferred opportunities for standardization across the nation:

- Standardize pavement markings to be 6 inches wide for all longitudinal markings on interstates, freeways, expressways, and principal arterials. For minor arterials and collectors, thinner striping could be allowed for speeds under 40 miles per hour.
- Use dotted edge-line extensions along ramps.
- Include chevron markings in gore areas (the triangular area located in between the lanes of a highway and either an entrance or an exit ramp).
- Use continuous markings for all work zone tapers.
- Eliminate Botts' Dots (non-reflective raised pavement markers) as a substitute for markings.
- Use high contrast markings on light-colored pavements.

[45] USDOT ITS JPO. Lesson Learned from Tampa (THEA) Connected Vehicle Pilot Wireless Backhaul Issues, July 2020. https://www.its.dot.gov/pilots/thea_cvp_wireless.htm
[46] Lu, Xialin. Infrastructure Requirements for Automated Driving. August 2018. Delft University of Technology
[47] Gold, Christian; Bengler, Klaus (2014): Taking Over Control from Highly Automated Vehicles. Proceedings of the 5th International Conference on Applied Human Factors and Ergonomics AHFE 2014, Kraków, Poland 19-23 July
[48] Verberne, F. M. F., Ham, J., & Midden, C. J. H. (2012). Trust in Smart Systems: Sharing Driving Goals and Giving Information to Increase Trustworthiness and Acceptability of Smart Systems in Cars. Human Factors: The Journal of the Human Factors and Ergonomics Society, 54(5), 799–810. doi:10.1177/001872081244382

- Minimize/eliminate confusing speed limit signs on parallel routes.

4.2. Consideration of market penetration 'tipping points' for enabled vehicles that causes agencies to invest in the necessary roadside and deskside hardware

This subject was identified as a key consideration for infrastructure investment. The research presented in this section attempts to address issues of market penetration, fleet mix, and adequacy of design standards for supporting AV and shared mobility options. The research team recognizes that different types of vehicles (shuttles, automobiles, commercial trucks, others) may have varying adoption timelines.

4.2.1 Market Penetration

Understanding when and where to invest in infrastructure to support new technologies in automated and shared mobility provides a set of rich research topics. Many researchers have explored the adoption of automated vehicle technology, including the individual-level factors for AV adoption and timing.[49] One of the most valuable lines of research for policy makers, however, is in the area of investment sequencing that builds upon these individual level factors. Research has proceeded on the potential sequencing of infrastructure investments. Requirements on current road infrastructure for high-level automated driving ultimately remain unclear.[50] [51] Farah and others used benchmarking, state of the practice survey, and a brainstorming workshop involving experts from different disciplines in the Netherlands, to develop a detailed mind map and recommendations for future research directions on this infrastructure sequencing issue.[52] Liu and Tight summarize the possibilities of infrastructure upgrades and propose a three-phase road infrastructure upgrade plan that evolves over time.[53] The first phase is maintenance, followed by a segregated-infrastructure expansion phase. This leads to phase three, which involves the application of simplified standards aimed at AV development. Other options for investment sequencing include starting with readily available improvements that offer benefits to human drivers and ADAS systems (e.g. improving lane marking and signage consistency).

Gopalswamy and Rathinam (2018) propose an "Infrastructure Enabled Autonomy" concept – with a distributed architecture that includes vehicle-to-everything (V2X) and other connectivity.[54] This approach is generally focused on concepts but provides some background on how to sequence along the lines of the Liu work. FHWA embarked on an assessment to understand

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[49] Asmussen, K.E., A. Mondal, and C.R. Bhat, "A Socio-Technical Model of Autonomous Vehicle Adoption Using Ranked Choice Stated Preference Data," Technical paper, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, July 2020.
[50] Lu, Xialin. Infrastructure Requirements for Automated Driving. August 2018. Delft University of Technology
[51] "Issue Overview: Infrastructure." Autonomous Vehicles Policy Initiative. Tabman Center at Harvard Kennedy School. https://www.hks.harvard.edu/sites/default/files/Taubman/AVPI/Infrastructure%20Basic.pdf
[52] Farah H., Erkens S.M., Alkim T., van Arem B. (2018) Infrastructure for Automated and Connected Driving: State of the Art and Future Research Directions. In: Meyer G., Beiker S. (eds) Road Vehicle Automation 4. Lecture Notes in Mobility. Springer, Cham
[53] Liu, Yuyan & Tight, Miles & Sun, Quanxin & Kang, Ruiyu. (2019). A systematic review: Road infrastructure requirement for Connected and Autonomous Vehicles (CAVs). Journal of Physics: Conference Series. 1187. 042073. 10.1088/1742-6596/1187/4/042073.
[54] Gopalswamy, Swaminathan and Rathinam, Sivakumar "Infrastructure Enabled Autonomy: A Distributed Intelligence Architecture for Autonomous Vehicles" 2018 IEEE Intelligent Vehicles Symposium (TTI)

the demands and potential impacts of automated vehicles both on current infrastructure assets, and on the future design of new infrastructure (publication pending in 2020). Kang and others developed a stated preference analysis extending understanding on the use of pooled shared mobility options, finding that educational and other socio-economic factors greatly influence mobility choices.[55]

Nitsche and others developed a set of government and infrastructure owner requirements for highly automated driving.[56] This framework includes observations based on the outcome of a literature review and a web questionnaire. Their research posited that clear, consistently placed, and harmonized lane markings and traffic signs, infrastructure-based warning systems for bad weather, roadside V2I/I2V (infrastructure to vehicle), pedestrian and bicyclist protections, and road surfaces with sufficient friction coefficients to allow emergency maneuvers are the primary infrastructure requirements for highly automated driving.

The European Union (EU) has also released a set of common requirements for infrastructure that focus on consistency.[57] The EU's Managing Automated Vehicles Enhances Network offers insight into opportunities related to communications and cellular infrastructure. It is developing infrastructure-assisted platoon organization and negotiation algorithms for such vehicle management at signalized intersections and corridors.[58]

To implement infrastructure upgrades for automated driving smoothly and successfully, stakeholders need to be engaged and the whole decision-making process should be open and flexible. KPMG used Byson's (2004) five levels of stakeholder involvement (Inform, Consult, Involve, Collaborate, and Empower) as a framework to develop the infrastructure requirements in its Autonomous Vehicles Readiness Index.[59] Stakeholder identification and perspective was included in work emerging from Delft.[60] These stakeholders also presented numerous "chicken and egg" arguments on infrastructure – namely shall we first allow the introduction of highly automated vehicles to the public roads or shall we finish the infrastructure upgrades first. USDOT prepared its AV framework which focuses on encouraging private

To implement infrastructure upgrades for automated driving smoothly and successfully, stakeholders need to be engaged and the whole decision-making process should be open and flexible

[55] Kang, S., A. Mondal, A.C. Bhat, and C.R. Bhat, "Pooled Versus Private Ride-Hailing: A Joint Revealed and Stated Preference Analysis Recognizing Psycho-Social Factors," Technical paper, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, July 2020

[56] P. Nitsche, I. Mocanu and M. Reinthaler, "Requirements on tomorrow's road infrastructure for highly automated driving," 2014 International Conference on Connected Vehicles and Expo (ICCVE), Vienna, 2014, pp. 939-940, doi: 10.1109/ICCVE.2014.7297694.

[57] Dimitris Milakis, Bart van Arem & Bert van Wee (2017) Policy and society related implications of automated driving: A review of literature and directions for future research, Journal of Intelligent Transportation Systems, 21:4, 324-348, DOI: 10.1080/15472450.2017.1291351

[58] https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-transport/automated-road-transport/maven

[59] 2019 Autonomous Vehicles Readiness Index, KPMG, https://assets.kpmg/content/dam/kpmg/xx/pdf/2019/02/2019-autonomous-vehicles-readiness-index.pdf

[60] Coordination of Automated Road Transport For Europe. Interactive Symposium on Research & Innovation for Connected & Automated Driving in Europe 19-20 April 2018, Vienna

investment and testing.[61] Additional work on infrastructure requirements was represented in the NCHRP study on rightsizing transportation infrastructure.[62]

It has been well described that the impacts of automated driving on the road infrastructure itself could be positive or negative based on the practical road and traffic conditions.[63] Much uncertainty remains and further clouds the ability to sequence investments and planning decisions. According to this study's analysis, the first Level 4 automated vehicle would likely be introduced to the market in the next five years, but a long period is needed before it is finally accepted by people and replaces the conventional vehicle in the future (from 2040-2060). Before the penetration rate of Level 4 automated vehicles reaches 100%, AVs should be capable of handling all mixed traffic situations as dedicated lanes may not be built due to their high cost and unknown influence on the traffic. Most of the current Level 4 vehicle tests focused on improving the technology of the vehicle to make it fit for the road environment as it exists today, not as it could potentially evolve into.[64]

Additional work on development of information and understanding on infrastructure sequencing and investment scenarios presents guidance for agencies considering minimal investments.[65] [66] There remain perceived safety concerns about mixed fleet environments.[67] These researchers also argue for increased consideration of testing and implementation rules and regulations to influence adoption of new technologies. Lane markings, sufficient friction coefficients, traffic signals at intersections in urban areas, and current standards for width (lane, shoulder, median, clear zone) are regarded as essential physical infrastructure requirements for Level 4 vehicles,

Many decision-makers and road authorities have wondered how to plan roads with automated vehicles and whether public policies should encourage or restrict their use

[61] "*USDOT Comprehensive Management Plan for Automated Vehicle Initiatives: US Department of Transportation." U.S. Department of Transportation. Accessed June 5, 2020.* https://www.transportation.gov/policy-initiatives/automated-vehicles/usdot-comprehensive-management-plan-automated-vehicle.
[62] Duncan, Chandler, Michael Brown, Naomi Stein, David Rowe, Danny Rotert, Michael David Hurst, Tim Lomax, Peter Hylton, Hugh McGee, and Anne Morris. Right-Sizing Transportation Investments: A Guidebook for Planning and Programming. No. Project 19-14. 2020. http://www.trb.org/Main/Blurbs/180145.aspx
[63] Chen, F., Balieu, R., & Kringos, N. (2016). Potential Influences on Long-Term Service Performance of Road Infrastructure by Automated Vehicles. Transportation Research Record: Journal Of The Transportation Research Board, 2550, 72-79.
[64] Ibid.
[65] Bittner, Jason and Silber, Hannah. Infrastructure requirements for AV. Technical Memorandum in support of Missouri DOT Long Range Transportation Plan Update. 2018
[66] "Blueprint for Autonomous Urbanism – Second Edition." National Association of City Transportation Officials (2019). https://nacto.org/publication/bau2/
[67] Nair, G.S. and C.R. Bhat, "Sharing the Road with Autonomous Vehicles: Perceived Safety and Regulatory Preferences," Technical paper, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, June 2020

while traffic signs could benefit automated vehicles but are not mandatory.[68]

The introduction of automated vehicles is expected to significantly affect the infrastructure, so infrastructure may need to be revolutionized alongside the vehicles themselves. Many decision-makers and road authorities have wondered how to plan roads with automated vehicles and whether public policies should encourage or restrict their use. Unfortunately, the research on systematic or sequenced infrastructure planning has not identified a clear path forward, understanding that a variety of factors play into the decision making at varying governmental levels.

Ultimately, the market penetration rates will require attempts to overcome customer barriers.[69] Extensive research already exists on AV ownership and use preferences.[70][71] The literature documents mixed public perceptions of AVs and shared mobility: barriers to acceptance of this technology ranges from fear and distrust to existing pervasive car culture. A 2019 AAA survey found that 71% of respondents are afraid to ride in fully self-driving vehicles.[72] Reception to automated vehicle technology in more limited applications, such as low-speed shuttles with a short range or fully automated delivery vehicles, was more positive. However, only 20% of respondents were comfortable with fully automated vehicles for loved ones. One study reported a gradual increase in the percentage of people comfortable with full self-driving automation from 2016 to 2018; however, the percentage of people only comfortable with no automation or features that activate only in certain situations such as in an emergency also increased, indicating a polarizing trend. Others have identified safety concerns associated with commercial trucking as the primary concern for larger public acceptance of vehicle automation.[73] Namely, this research held that passenger vehicle operators did not want to be traveling alongside an automated heavy commercial truck.

With respect to infrastructure sequencing and understanding tipping points at which government investment is necessary or warranted, there are many uncertainties and gaps in the reviewed literature and ongoing research efforts. These include:

- Improved understanding of the ability of AVs to effectively respond to the current roadway environment and visible pavement, bridge, and culvert defects and deficiencies like potholes, cracking, faulting, etc.
- Quantification and comparison of varying impacts of AVs on pavements, bridges, and culverts, including the impacts from potential changes to traffic speeds of AVs.
- Impacts of mixed traffic (e.g., AVs, manually driven vehicles, trucks) on long-term pavement and bridge/culvert performance.

[68] Farah, H., Erkens, S., Alkim, T., & van Arem, B. (2016). Infrastructure for Automated and Connected Driving: State of the Art and Future Research Directions (pp. 189-190). Berlin: Springer.
[69] Raj, A., Kumar, A., and Bansal, P.: A multicriteria decision making approach to study barriers to the adoption of autonomous vehicles. Transportation Research Part A: Policy and Practice. 133: 122-137 (2020).
[70] Dong, X., DiScenna, M., and Guerra, E. (2019). Transit user perceptions of driverless buses. Transportation, 46(1), 35–50. https://doi.org/10.1007/s11116-017-9786-y
[71] Nair, G. S., Astroza, S., Bhat, C. R., Khoeini, S., and Pendyala, R. M. (2018). An application of a rank ordered probit modeling approach to understanding level of interest in autonomous vehicles. Transportation, 45(6), 1623–1637. https://doi.org/10.1007/s11116-018-9945-9
[72] AAA 2019 survey of AV readiness and interest
[73] Viscelli, S. (2018). Driverless? Autonomous trucks and the future of the American trucker. https://trid.trb.org/view/1540733

- Adequacy of current pavement and structure design standards and tools, maintenance strategies, and asset management techniques to effectively address the potential impacts of AVs on roadway infrastructure.

4.3. Potential upgrades to transportation infrastructure, such as embedded sensors, cameras, bike stations, electronic tolls, adaptive traffic signals, etc., that can enhance the travel experience and the effect of infrastructure on supply and demand for transportation services

This section describes research on potential infrastructure upgrades that would serve as enablers for AV and shared mobility. The rapid evolution and regular maintenance needs of vehicle sensors for highly automated vehicles (such as lane detection, vehicle awareness, or radar and infrared sensors) likely favor fleet operations in the near term and create challenges to future proofing infrastructure. Sensors on the infrastructure side face their own challenges. Technological obsolescence coupled with traditional infrastructure procurement delays do not provide many opportunities for infrastructure owners to get in front of this curve.[74] Compared to the older units, new products have higher performance metrics compared to the older units, such as reliability, resilience, memory capacity, improved material, precision, artificial intelligence, lower energy consumption, ergonomics, and safety. Nonetheless, when should investments be made?[75] Sensors, for example, are a critical but costly component as minor impacts can damage or destroy sensors, leading to diminished sensor performance and high sensor turnover rates.

The MUTCD defines the standards used by road managers nationwide to install and maintain traffic control devices FHWA has efforts underway to support ADAS technologies, such as lane departure warning, lane keep assist, and sign recognition that would rely on these new sensors and technology. Interoperability across agencies is a critical piece of the successful deployment of these emerging connected and automated technologies and the research needs are substantial for comparing existing MUTCD information with new and emerging needs for highly automated vehicles.

In general, there are dozens of potential sensors that could provide a range of information to highly automated and shared use vehicles. Friction, weather, pavement condition, lane delineation, and other sensors are presently available. Cost concerns and durability/reliability issues remain. Overall, the public sector has typically been slow to adopt new technology.[76] There is some research demonstrating concerns about installation and procurement of these

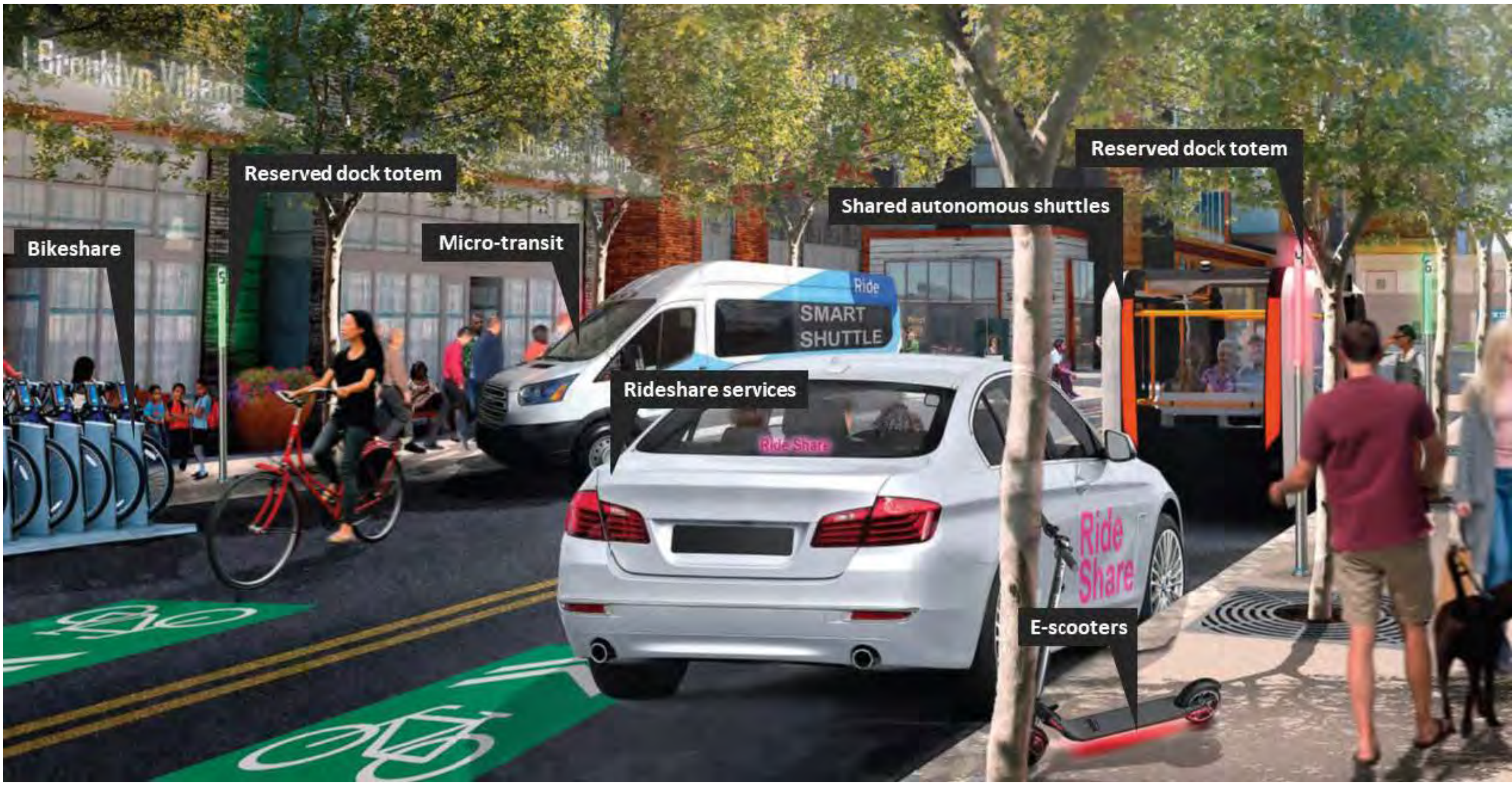
[74] Huang, Yu-Lin, and Chia-Chi Pi. "Competition, dedicated assets, and technological obsolescence in multistage infrastructure investments: A sequential compound option valuation." *IEEE Transactions on Engineering Management* 58.1 (2010): 141-153.
[75] Mellal, Mohamed Arezki. "Obsolescence–A review of the literature." *Technology in Society* (2020): 101347.
[76] Slade, Giles. *Made to break: Technology and obsolescence in America*. Harvard University Press, 2009.

technologies in the face of technological change, requiring detailed planning efforts for new approaches.[77]

Traffic cameras have been used to assist in incident response and general traffic management. Driver monitoring is a critical component for enabling new technologies and adoption. Expanded use may encourage additional use of shared mobility options, providing extra degrees of safety and monitoring.[78]

One area for potential further study is on inter-urban dedicated lanes for long haul automated trucking. Several research efforts have identified trucking as a potential early investment opportunity.

Our team located little research on potential upgrades for bike stations or electronic tolling as a driver for automated technology or shared mobility options. Shared bike usage rises dramatically as stations become ubiquitous, but there is no known relationship for AV expansion.



[77] Smith, Bryant Walker. "A legal perspective on three misconceptions in vehicle automation." *Road vehicle automation*. Springer, Cham, 2014. 85-91.
[78] Verpraet, Illya. Why driver monitoring is crucial to AV safety. Autonomous Vehicle Interior Design & Technology Symposium, May 21-23, Stuttgart, Germany 2019.

4.4 Influence of infrastructure on promotion of new mobility innovation, including electric vehicles; at what point is there enough market penetration to justify infrastructure investments?

4.4.1 Electric Vehicles

There has been limited research completed on the exact market penetration points for advancing infrastructure investments. Hundreds of communities have invested in charging locations, retail establishments have installed charging stations in parking facilities, and airports have reserved spaces for electric vehicle users as value added propositions.

Traditional fuel price and vehicle cost remains a primary driver for market penetration for electric vehicles.[79] Recent research shows there is an increased demand based on environmental concerns, including climate change.[80] Some research outlined as much as a 40% weight to environmental concerns in the purchase decision.[81] Demand for electric vehicles has been difficult to predict.[82]

4.4.2 Shared Mobility

Most shared mobility platforms require no new infrastructure. Additional bike lanes have not proven to increase use of shared bicycles outside of anecdotal analysis. Airports have located TNCs in certain designated pick up and drop off locations. Some cities have allowed for dedicated parking stalls for electric, hybrid, shared, and community vehicles. No research was identified specifically targeting these infrastructure investments for these uses.

4.4.3 Parking Infrastructure and Curb Management

One of the anticipated advantages of CAVs (and the increased uses of shared mobility technologies) is dropping passengers right at their destinations, then moving to a parking or staging area. This requires some changes to the current parking lots and meters infrastructure. Since CAVs may not have humans on board, the common payment methods at parking lots and on street parking will not be applicable for them. Privately owned AVs would likely drive to lots on the urban perimeter rather than parking in the center city, increasing outlying parking demand.

Automated payment methods should be facilitated. The entrance gates at parking lots and the parking meters on streets should be capable of recognizing vehicles. This can be handled through the use of an RFID reader at these points, and an RFID tag on each vehicle. The reader will be able to automatically retrieve the vehicle license plate number stored in its tag.

Parking issues remain a concern: pricing schemes could limit the ability of increased usage for AVs.[83] This study showed that if costs associated with parking requirements were increased to

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[79] Gomez Vilchez, Jonatan J., et al. "Electric car purchase price as a factor determining consumers' choice and their views on incentives in Europe." *Sustainability* 11.22 (2019): 6357.
[80] Transportation Research Board and National Research Council. 2015. Overcoming Barriers to Deployment of Plug-in Electric Vehicles. Washington, DC: The National Academies Press. https://doi.org/10.17226/21725.
[81] Tu, Jui-Che, and Chun Yang. "Key factors influencing consumers' purchase of electric vehicles." *Sustainability* 11.14 (2019): 3863.
[82] Raj (2020)
[83] Millard-Ball, Adam. "The autonomous vehicle parking problem." Transport Policy 75 (2019): 99-108.

any extent, consumers would not move trips to an AV. Cities could pass new curbside management plans committing any space savings from reduced parking or lane requirements to public use – or other uses. Cities use curbside space for parklets, green infrastructure, bus lanes, bike lanes, and small-scale vendors and kiosks.[84][85] AVs can affect future parking demands in many ways.[86][87] These issues all remain largely speculated rather than firmly researched.[88]

As noted in other Topical Papers in this series, AVs and shared mobility are likely to increase demand for the curb, whether for parking, drop-off, or deliveries. This can be mitigated through parking and curb management policies such as eliminating minimum parking requirements, intelligently pricing curb spaces, and instituting parking cash-out strategies.[89] Congestion from shared mobility service can be mitigated through regulation of parking and right-of-way access, whether by requiring paid access to loading zones, use of municipal requests for proposals for right-of-way-access, or otherwise designating parking or drop-off zones for private use.[90][91] One recommendation is to create a detailed asset map of curbs and curb-side regulations including loading zones and parking areas for regulatory, maintenance, and management purposes.[92]

4.5 The role governance has when considering infrastructure issues, including defining spaces in communities and right of way management

Changes in ownership, organizational structure and operation of transport infrastructures might appear when fully automated vehicles (level 4 or 5) increase considerably their share in the vehicle fleet. Understanding the infrastructure sequencing needs is essential for the development of a well-designed rollout of new technologies for transportation. [93] Changes to right of way management practices, parking requirements, curb setbacks, and other elements could include a segmentation of the road network, operation and maintenance by private

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84 NACTO Blueprint for Autonomous Urbanism: Second Edition. https://nacto.org/publication/bau2/
85 "Ten Rules for Cities About Automated Vehicles." Congress for New Urbanism, October 2017. https://www.cnu.org/publicsquare/2017/10/16/ten-rules-cities-about-automated-vehicles
86 Esther González-González, Soledad Nogués and Dominic Stead (2020), Parking Futures: Preparing European Cities for the Advent of Automated Vehicles, Land Use Policy, Vol. 90 (https://doi.org/10.1016/j.landusepol.2019.05.029).(https://doi.org/10.1016/j.landusepol.2019.05.029).
87 Marsden, G., Iain Docherty and R. Dowling. “Parking futures: Curbside management in the era of ‘new mobility’ services in British and Australian cities.” Land Use Policy 91 (2020): 104012.
88 Benelli, Giuliano & Pozzebon, Alessandro. (2013). Innovative Solutions for the Automatic Payment of Car Parks. International Journal for Infonomics. Special 1. 828-834. 10.20533/iji.1742.4712.2013.0098.
89 Vaidyanathan, Shruti. "Shaping Autonomous Vehicle Deployment to Meet Climate and Energy Goals: A Policy Toolkit for Cities." (2019).
90 Bailo, Carla, Kristin Dziczek, Brett Smith, Adela Spulber, Yen Chen, and Michael Schultz. "The Great Divide: What Consumers Are Buying vs. The Investments Automakers & Suppliers Are Making in Future Technologies, Products & Business Models." *Center for Automotive Research: Ann Arbor, MI, USA* (2018): 1-33.
91 Spulber, Adela, E. P. Dennis, R. Wallace, and M. Schultz. "The impact of new mobility services on the automotive industry." *Center for Automotive Research* (2016): 1-56.
92 “Where Are Self-Driving Cars Taking Us?” Union of Concerned Scientists, 2019. https://www.ucsusa.org/resources/where-are-self-driving-cars-taking-us.
93 Mervis, Jeffrey, Gretchen Vogel, Jennifer Couzin-Frankel May, Ann GibbonsMay, Meredith Wadman, Jon Cohen, Warren Cornwall, et al. “Are We Going Too Fast on Driverless Cars?” Science, December 14, 2017.

organizations and the emergence of transportation providers that could guarantee trip quality, regardless of the travel mode.[94]

There appears to be some desire for priority treatments for transit operations, truck platooning, and managed lanes presently to provide future AV operations.[95] OEMs are focused on two paths of AV deployment at present: (1) consumer AVs that will build incrementally on SAE level 2 to eliminate driver "pain points," and (2) professionally managed level SAE Level 4 fleets operating in constrained environments (often within cities). The fleet approach is the more transformational of the two paths.

4.6 Issues associated with 5.9GHz spectrum allocation and impacts on safety

The arrival of self-driving and connected cars will add weight to the case for improved highway maintenance, not only to tackle the huge backlog, but also to ensure the associated communication and information systems are up to standard and offer comprehensive coverage.[96] Not all are in agreement about the need for connectivity in this way.[97]

In the US, the 5.9 GHz band had been reserved for a modified version of the Wireless Local Area Network protocol, IEEE802.11p dedicated short-range communications (DSRC). This "safety band" was designated to allow vehicle-to-vehicle and other communications of critical safety data. As the use in this band was slow to rollout, many advocated for opening the band to other uses. The USDOT has expressed "significant concerns" with a Federal Communications Commission (FCC) proposal to change acceptable uses of the 5.9 GHz section. In published statements, the move "jeopardizes the significant transportation safety benefits that the allocation of this band was meant to foster."[98] Other spectrum bands are possibly more effective for certain automation technologies. For example, the FCC has cited that long-range radar systems in the 76-81 GHz band are especially useful for automatic emergency braking systems and adaptive cruise control systems.[99]

The 5.9 GHz band has been reserved for public use for DSRC communications. Several research activities have explored the use of this spectrum for safety applications. A University of Virginia team explored use of FHWA's Road Weather Management Program data to improve connected vehicle decision making. As part of its Connected Vehicle Pilot Deployment Program, USDOT awarded funding for pilot sites in New York City, Wyoming, and Tampa to implement a suite of V2I, V2V, and V2X applications in selected areas (e.g., in city intersections and along state highways).

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[94] Van Arem, Bart, and Cyprian A. Smits. An exploration of the development of automated vehicle guidance systems. No. 97/NV/294. 1997.
[95] FHWA Impacts of Automated Vehicles on Highway Infrastructure
[96] Johnson C. Readiness of the Road Network for Connected and Autonomous Vehicles. 2017. http://www.racfoundation.org/research/mobility/readiness-of-the-road-network-for-connected-and-autonomous-vehicles
[97] Smith B.W. (2014) A Legal Perspective on Three Misconceptions in Vehicle Automation. In: Meyer G., Beiker S. (eds) Road Vehicle Automation. Lecture Notes in Mobility. Springer, Cham. https://doi.org/10.1007/978-3-319-05990-7_8
[98] https://www.fiercewireless.com/wireless/rift-over-5-9-ghz-grows-as-lawmakers-express-alarm-over-fcc-s-plans
[99] Paul Pickering, The Radar Technology Behind Autonomous Vehicles, ECN (Dec. 7, 2017) https://www.ecnmag.com/article/2017/12/radar-technology-behind-autonomous-vehicles. See also Continental AG, Continental's Next Generation Radar Technology Enables New Safety Features (Aug, 19, 2019)

Two distinct camps emerge on the issue of vehicle connectivity using existing radiofrequency spectrums. Short range technologies (including DSRC) and cellular technologies. A pilot study was conducted at the University of Michigan to examine the feasibility of V2V communication in a large-scale, real-world environment.[100] Research has shown that safety messages perform better on the short range while other types of messages can use the cellular network more effectively.[101] 4G-LTE was preferred for the non-safety applications, such as traffic information transmission, file download, or Internet accessing, which does not necessarily require the high-speed real-time communication that the safety applications like Collision Avoidance or electronic traffic signs require. Others held that IEEE 802.11p offers acceptable performance for sparse network topologies with limited mobility support while cellular LTE meets most of the application requirements regarding reliability, scalability, and mobility support.[102]

Research proposed a theoretical framework which compares the basic patterns of both DSRC and LTE in the context of the safety of life vehicular scenarios. According to the numerical experiments, the author concludes that the abilities of LTE to support beaconing for vehicular safety applications are poor as the LTE network easily becomes overloaded even under the idealistic assumptions.[103] DSRC has low scalability – the protocol is unable to provide the required time-probabilistic characteristics when travelling in a dense traffic.[104]

Additional research on the utility of each and the acceptability and utility of any messaging associated with them would be valuable inputs for advancing connected vehicle technology. The dedication of specific frequencies and removal of uncertainty could enable advanced development of connected vehicle technologies. The FCC has cited uncertainty as a limiting force for OEMs in the development of new connected vehicle technologies. The Alliance of Automobile Manufactures asserted that “repeated spectrum sharing proposals by the FCC have induced ongoing uncertainty within the 5.9 GHz band” and that “[a]s a result of continued lack of clarity about unlicensed spectrum sharing in the 5.9 GHz band, planned deployments of V2X technologies have been halted, and the future of the 5.9 GHz band for ITS applications remains unpredictable.”[105]

4.7 Infrastructure Features and Operation of AVs

[100] B. Schoettle and M. Sivak, “A survey of public opinion about connected vehicles in the U.S., the U.K., and Australia,” in Proceedings of the 3rd International Conference on Connected Vehicles and Expo (ICCVE '14), pp. 687–692, November 2014.
[101] Zhigang Xu, Xiaochi Li, Xiangmo Zhao, Michael H. Zhang, Zhongren Wang, "DSRC versus 4G-LTE for Connected Vehicle Applications: A Study on Field Experiments of Vehicular Communication Performance", Journal of Advanced Transportation, vol. 2017, Article ID 2750452, 10 pages, 2017. https://doi.org/10.1155/2017/2750452
[102] Z. H. Mir and F. Filali, “LTE and IEEE 802.11p for vehicular networking: a performance evaluation,” EURASIP Journal on Wireless Communications and Networking, no. 89, pp. 1–15, 2014.
[103] A. Vinel, “3GPP LTE versus IEEE 802.11p/WAVE: which technology is able to support cooperative vehicular safety applications?” IEEE Wireless Communications Letters, vol. 1, no. 2, pp. 125–128, 2012.
[104] S. Lee and A. Lim, “An empirical study on ad hoc performance of DSRC and Wi-Fi vehicular communications,” International Journal of Distributed Sensor Networks, vol. 9, pp. 1–10, 2013.
[105] Federal Communications Commission. Notice of Proposed Rulemaking – ET Docket No. 19-138. Use of the 5.850-5.925 GHz Band, November 21, 2019. https://docs.fcc.gov/public/attachments/DOC-360940A1.pdf.

Several studies have explored physical infrastructure enablers to enhance the development of AVs.[106] [107][108] Repairs of potholes and other structural deficiencies across pavements remains are important for overall ride quality as ever before.[109] Researchers identified a mix of features that would enable use of advanced technology to supplement the driving environment. These features include a framework that highlights critical features ranging from visibility and connectivity to technology supported equipment and processes to overall ubiquity.

Digital infrastructure is becoming an equally important element distinguishing the readiness of the public system to accept emerging AV technologies. This digital infrastructure includes the static and dynamic digital representation of the physical world with which the automated vehicle will interact to operate.[110] Data frameworks are being developed under NCHRP project 08-116 Framework for Managing Data from Emerging Transportation Technologies to Support Decision-Making that structures the process for identifying, collecting, aggregating, analyzing, and disseminating data from emerging public and private transportation technologies. An implementation study is forthcoming in 2021. The aforementioned research on connectivity and spectrum issues remain essential. Road-side digital infrastructure can meet various forms of connectivity requirements, including those connected sensors described previously in as infrastructure upgrades. These can include advanced performance sensors as well as basic devices such as loop detectors and magnetic detectors and over-roadway sensors (e.g. cameras, radars and ultrasonic sensors.)[111] One additional digital infrastructure line of research is to make future digital infrastructure easier to realize in the future, by making upgrades today (conduit installation, right of way protection, etc.).[112][113]

4.7.1 Rutting Issues

Perhaps the most direct impact automated vehicles have on the physical infrastructure relates to rutting. Rutting is a settling condition of pavements caused by repeated loading in the same track. Automated vehicles with less wandering make asphalt pavement more prone to the rutting.[114] Wheel wander and distribution patterns, coupled with lane capacity, and traffic speed affect pavement rutting performance.[115] It also can require updated practices and models for understanding pavement fatigue and hydroplaning potential. Depending on the implementation of AV technologies, platooning and positioning (particularly of autonomous trucks) may impact

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106 "Autonomous Vehicle Innovation Network (AVIN)."Features of the Infrastructure Facilitating the Operation of CAVs" November 2018. Autonomous Vehicle Innovation Network (AVIN). Accessed May, 2020. https://avinhub.ca/.
107 Autonomous Vehicle Innovation Network (AVIN). (2018). Regional Technology Development Sites: Technology Focus Areas. Retrieved from https://bit.ly/2DAWXcZ
108 "Autonomous Vehicle Policy Framework Summit." Transpogroup, February 2018. http://www.transpogroup.com/assets/autonomousvehiclepolicyframeworksummit_finalproductreport.pdf
109 Carlson, Paul.
110 https://connectedautomateddriving.eu/mediaroom/digital-infrastructure-automated-vehicles/
111 Lyon B, Hudson N, Twycross M, Finn D, Porter S, Maklary Z and Waller T 2017 Automated vehicles: Do we know which road to take? Infrastructure Partnerships Australia
112 Johnson C 2017 Readiness of the road network for connected and autonomous vehicle. London: RAC Foundation.
113 TSC 2017a Future Proofing Infrastructure for Connected and Autonomous Vehicles. https://s3-eu-west-1.amazonaws.com/media.ts.catapult/wp-content/uploads/2017/04/251153 13/ATS40-Future-Proofing-Infrastructure-for-CAVs.pdf.
114 Bastola, Nitish and Souliman, Mena, Rutting Performance of Pavement Under Autonomous Vehicle Consideration, University of Texas Tyler, 2019. scholarworks.uttyler.edu/cgi/viewcontent.cgi?filename=0&article=1051&context=lyceum2020&type=additional
115 Chen F, Baileu R and Kringos N 2016 'Potential influences on long-term service performance of road infrastructure by Automated Vehicles'. Transportation Research Board. pp. 72–79. DOI: 10.3141/2550-10.

the condition and long-term performance of pavements as they relate to rutting.[116] There are limited studies presently available to adequately assess the current actual impacts of AVs on highway infrastructure, including on how AV implementation and operation will affect pavement and bridge designs, maintenance, and asset management strategies. Researchers at Virginia Tech found that to reduce the negative impact of AVs on pavement life, an optimal AV wandering pattern needs to be programmed in a uniform distribution, which results in prolonged pavement life and decreased hydroplaning potential.[117]

One potential solution from the infrastructure owner point of view would be the use of reinforced pavements. Certain areas beneath the roadway operation track could be strengthened. These are a cost concern. Better understanding changes in vehicle class and axle load distributions and wander resulting from AV introduction, and their associated impacts on pavements, bridges, and culverts could help.

Concrete walls such as dividers should be marked with highly reflective markers, especially in the beginning section to enhance the visibility. These barrier and road separations should be clearly differentiated with good contrast between the barrier and road. Steel-rope-barriers are less visible than steel-beam-barriers by computer vision – but rope barriers are highly effective at preventing cross over crashes. Steel-beam barriers or concrete walls with clear reflective markings are preferred.[118]

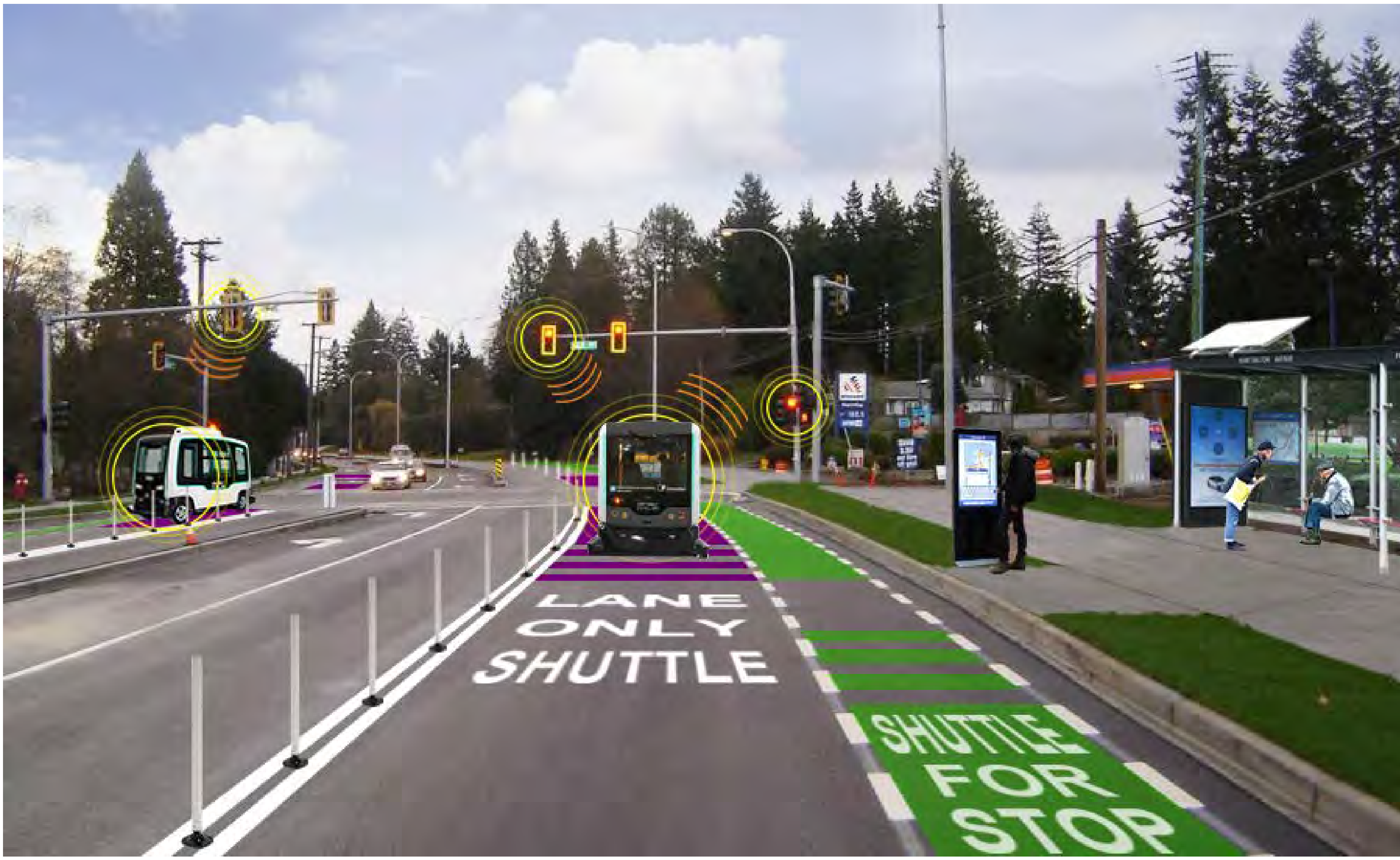
[116] Bittner, Jason and Silber, Hannah. Infrastructure requirements for AV. Technical Memorandum in support of Missouri DOT Long Range Transportation Plan Update. 2018
[117] Zhou, Fujie, Hu Sheng, Wenjing Xue, and Gerardo Flintsch. Optimizing the Lateral Wandering of Automated Vehicles to Improve Roadway Safety and Pavement Life, Safety through Disruption (Safe-D) National University Transportation Center, December 2019. 69A3551747115/Project 02-008
[118] FHWA Infrastructure Readiness (2019)

4.7.2 Safety Infrastructure

With Level 4 AVs, some safety measures in traditional road infrastructure design (such as wide lanes, shoulders, guardrails, rumble strips) could possibly be reduced[119]. As noted previously redesigns of lane width can be accomplished at advanced market penetration levels. Other elements of safety research include discussions on guardrails and shoulders.[120]

These safety devices are not seen as an enabling technology for increasing AV usage. Their contributions to crash safety improvements during mixed fleet transitions and future scenarios remain valuable. During this period of transition, for the technology to improve, it must be exposed to real, on-road conditions, and that will include safety infrastructure as noted.

Some concerns over consistent marking of jersey barriers, and other temporary safety devices, is discussed further in the work zone area.



[119] Somers, A., & Weeratunga, K. (2015). Automated vehicles: are we ready? Internal report on potential implications for Main Roads WA.
[120] Büchsner, M., Reichenbach, M. "Safety technology is an enabler for autonomous driving". ATZ Worldw 121, 22–25 (2019). https://doi.org/10.1007/s38311-018-0214-5

4.7.3 Dedicated Lanes

State DOTs maintain and operate highway infrastructure, and thus would be responsible for any investments in intelligent infrastructure or the creation and operation of dedicated lanes for AVs.[121] Dedicated lanes are often debated as a potential means to separate the automated vehicles from human operated vehicles, as well as being able to maximize the benefits of reduced lane widths, increased vehicle spacing, and other operational improvements.

4.7.4 Work Zones

FHWA has supported several technologies in its smart work zones effort.[122] A "smart work zone system" is the application of computers, communications, and sensor technology to freeway transportation and would possess the following general characteristics:

- Real-time: The system obtains and analyzes traffic flow data in real-time, providing frequently updated information to motorists.
- Portable: The system is portable, hence allowing its installation (with minor modifications as necessary) at different locations.
- Automated: The system operates in an automated manner with as minimal supervision as possible by human operators.
- Reliable: The system provides accurate and reliable information, keeping in mind the serious consequences of misinforming motorists in work zone situations.

This smart work zone effort would include automated work zone information systems, including speed warnings and advisories. For AVs, the essential enabling technology is up to date information and consistent use of traffic control around work zones. In addition, FHWA has sponsored research efforts enabling data sharing from work zones through the ITS joint program office. The Work Zone Data Exchange attempts to harmonize work zone data for use by third parties.[123] The Texas Department of Transportation uses the Work Zone Data Exchange specification to report lane closures statewide through a single feed.

FHWA is leading efforts, via the Work Zone Data Initiative, to develop a standard approach for collecting, organizing, and sharing data on the “when”, “where,” and “how” of work zone deployment.[124] The effort is designed to share work zone information easily across a broad spectrum of end users.

Other emerging lessons from the research include use of beacons for marking work zones electronically.[125] Electronic beacons that direct AVs through work zones with missing, illegible, non-reflective, or conflicting pavement markings are being developed.[126] Machine vision research notes that cones on construction sites should be equipped with good reflective materials/stickers of a sufficient size for a good detection rate by computer vision even in rain

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121 Clark, B., Parkhurst, G., and Ricci, M.: Understanding the socioeconomic adoption scenarios for autonomous vehicles: a literature review. Project Report. University of West England, Bristol, UK (2016).

122 https://ops.fhwa.dot.gov/wz/workshops/accessible/Pant_paper.htm

123 USDOT Work Zone Data Exchange (WZDx), https://www.transportation.gov/av/data/wzdx

124 https://collaboration.fhwa.dot.gov/wzmp/wzdi/Forms/AllItems.aspx

125 Liao, Chen-Fu. Test and Evaluate a Bluetooth Based In-Vehicle Message System to Alert Motorists in Work Zones, University of Minnesota Center for Transportation Studies. May 2019.

126 Owen Hitchcock, Kristin Kersavage, Lingyu Li, Xiao Liang, Xu Lin. “Electronic Beacon to Guide Autonomous Vehicles through Work Zones. Pennsylvania State University,

and at night. We were unable to identify a published research effort specifically testing this approach. This is an area in need of additional research.

4.7.5 Climate change impacts

Limited research was discovered on infrastructure's impact on climate change mitigation and adaptation as it relates to automated vehicles and shared mobility. Transportation remains a primary cause of air pollution and climate change emissions released into the atmosphere, due to reliance on combustion to provide energy for transportation. CAVs could impact emissions from transportation by changing the amount of energy used in the transportation of goods and people, or by influencing the technology employed by CAVs to use that energy (combustion or electric). When operated with vehicle efficiency as one of the goals, CAVs can reduce energy consumption at all levels of automation.[127] The projects that make up ARPA-E's NEXTCAR Program, short for "NEXT-Generation Energy Technologies for Connected and Automated On-Road Vehicles," are enabling technologies that use connectivity and automation to co-optimize vehicle dynamic controls and powertrain operation, thereby reducing energy consumption of the vehicle.

As discussed in other Topical Papers, however, AVs can also increase miles driven, which increases total energy use.[128] Due to dependency on fossil fuels, conventional internal-combustion engine vehicles are a major source of air pollution and climate change emissions. Achieving deep greenhouse gas (GHG) reduction targets requires zero-emission transportation. Zero-emission vehicles (electric and fuel cell) are developing rapidly, and their penetration is rising throughout the world.

Connected automated electric vehicle (CAEV) technologies could play a role in the emerging transformation to sustainable low-carbon mobility, if electric propulsion is chosen by automakers as the preferred system for automation, or if it is chosen by individual or fleet owners for its cost and other benefits, or if electric propulsion in CAVs is mandated by government regulation. Charging and refueling of fully autonomous vehicles, regardless of whether they are electric, hydrogen or petroleum fuel, will either need to be automated or accomplished by a fueling attendant. This will necessitate infrastructure modification for autonomous refueling in particular.

CAEVs can result in major reductions in GHG emissions and be at the forefront of rapid transformation in transportation. CAEVs also have great potential to operate with higher vehicle efficiency, if they are charged using renewable energy sources that will significantly reduce emissions and dependency on fossil fuels.[129]

4.7.6 Rural and urban differences

With respect to infrastructure needs, we were unable to identify existing work that looked at urban and rural differences for infrastructure enablers. Based on industry conversations and prior conversations with state transportation officials, rural challenges remain for automated technologies, including roadway conditions, limited markings, narrow bridges, humps, and other infrastructure elements. DriveOhio, an initiative of the Ohio Department of Transportation focused on automated and connected transportation technologies, was awarded a 2019 demonstration grant to test, develop, and deploy automated transportation solutions focused on

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[127] https://arpa-e.energy.gov/?q=arpa-e-programs/nextcar
[128] SMART Mobility Capstone Report: Connected and Automated Vehicles, July 2020. US Department Of Energy. https://www.energy.gov/sites/prod/files/2020/08/f77/SMART-CAVS_Capstone_07.22.20.pdf
[129] Bittner, Jason (2019) Missouri DOT Automated Vehicles Strategy 2020-2040

rural roads and highways. This project will focus on running AVs on roads in 32 counties in the state's Appalachian region, including on unpaved roads. The testing will occur in all seasons, day or night and in challenging conditions including work zones. Iowa State University and Iowa DOT are partnering on a project called “Automated Driving Systems for Rural America.”[130] This project will focus on unique challenges for driverless technology on rural roads, including climate, weather, road variance, slow-moving traffic, sharp curves, steep grades, limited visibility and loose surfaces. Texas A&M University recently started a project to develop and test automated driving systems for rural roads without high-definition maps and with no or low-quality road signs or markings. All three of these efforts were awarded under the USDOT’s Automated Driving Systems Demonstration Grant program.[131]

4.7.6 Transportation System Management and Operations

There are a number of infrastructure focused observations emerging from best practices research in transportation system management and operations. The National Operations Center of Excellence established the Research in Operations database as a centralized, on-line repository for sharing and rating new transportation operations research. The FHWA Office of Operations provides research on V2I deployments and ITS standards, including architecture and systems engineering efforts.[132] These projects also include data access and data sharing. The FHWA’s Office of Operations Research and Development has also advanced a number of projects specific to Transportation Enabling Technologies. Examples of infrastructure focused enabling technologies include communication systems, enhanced global positioning systems, traffic systems control algorithms, and traffic sensors.

[130] https://now.uiowa.edu/2019/09/federal-grant-help-nads-study-automated-vehicles-rural-roads
[131] https://www.transportation.gov/av/grants
[132] https://ops.fhwa.dot.gov/int_its_deployment/index.htm

5 Further Research Opportunities

The suggestions below identify topics for future research to inform and focus the important discussion around *Infrastructure Enablers for Automated Vehicles and Shared Mobility*. These topics will be evaluated by the Forum in coordination with the appropriate TRB Committees and staff to determine which topics can be expanded into more detailed research statements and proposals. Where possible, crossover to other Topical Papers has been identified to assist with the development of more robust and cross-issue research statements.

Subtopic(s)	Research Opportunity	Crossover to Other Topics
4.1	Develop a new "design driver" to the roadways that would allow for additional discussion on the existing standards. Sign standards and protocols for spacing will also help. Potential research questions could include: • Are there unifying standards appropriate for human and machine-based "design drivers"? • What MUTCD flexibility in design needs to be tightened to improve traffic controls? • Is there a need for increased redundancy in sign placement? • What types of devices can be used for sign recognition or traffic signal placements?	*None*
4.1	Standardize machine vision and visibility standards across relevant sources. One cited example of light emitting diodes shows the challenges, as the LED technology has different sensory requirements than traditional incandescent lighting. Some additional research questions could include: • What is the impact of new signs on human performance? Are there unforeseen consequences associated with these changes? • How are colors interpreted? Does it make a difference for either the human driver or machine vision-based equipment? • Can machine vision be improved for inclement weather and inadequate lighting?	*None*
4.1	Quantify the return on investment of making national changes (in design and/or maintenance) to any physical infrastructure element, but particularly pavement markings. • Include investigating the right level of service for pavement markings would benefit transportation policy makers	*None*
4.2 4.7	Conduct an assessment of the utility of dedicated lanes during mixed fleet operations including return on investment study utility and feasibility of this approach to enable advanced technologies.	*None*
4.2	Evaluate what devices and sensors should be approved for purchase and installation on the National Highway System and other network components.	*None*
4.3	Assess the total costs of transportation infrastructure upgrades and modifications plus identify funding strategies to promote proactive planning and investment. In addition, a study on potential truck platooning and impact on structural loading is likely necessary.	*Freight*

Subtopic	Research Opportunity	Crossover to Other Topics
4.7	Digital Infrastructure: Assess data frameworks and other digital infrastructure that could enable AVs and shared mobility. Among the research areas that could be considered are: • How can data frameworks be used to advance the state of the practice for advanced driver assistance systems and AVs/shared mobility options? • Are there specific needs emerging from the demonstration projects related to the digital spectrum for DSRC and other safety messages? • How do we avoid a “digital divide” between communities and states that make advanced infrastructure investments? • Are there additional investments that the public sector side needs to consider, beyond fiber optics, to enable new technologies? What is the sequencing of said investments?	*Data sharing*
4.7	Create best practices guidance for managing work zone markings, cone/barrel placements, duration, and other elements that can be used to support improved operations for AV and shared mobility providers. Some research questions could include: • What are effective communication tools? • Are there standardized equipment markings, colors, sign placements that would benefit AVs? • How do AVs respond to human presence in work zones versus pedestrians to determine expected behaviors? • Are vehicles used in construction areas properly categorized through machine vision? • Are real-time databases of work zone activity feasible? • How can we equip workers safety equipment (vests, hard hats, etc.) with V2X devices to communicate with vehicles?	*Safety*

Subtopic	Research Opportunity	Crossover to Other Topics
4.7	Quantify and compare varying impacts of AVs on pavements, bridges, and culverts, including those from the increased traffic speeds of AVs. Some potential research questions include: • What is the impact on rutting and pavement performance for repeated loads? • Are there highway designs that perform better? • Could lane widths be reduced or changed in the near future? • What is the return on investment of on pavement changes to reflect these future uses? • What is the level of service necessary to facilitate AV movements? • Will AVs require increased design speeds?	*None*
4.7	Develop best practice guidance and standard for infrastructure in rural applications, including changes to lane markings, uncontrolled intersections, and high speed two lane rural highways. Among the research areas that could be considered are: • What is the responsiveness of AV technologies on unpaved roadways and roadways with limited pavement markings? • How should low volume roads maintenance standards be updated to accommodate HAVs and shared mobility vehicles? • How can AVs respond to single lane structures and lane keeping without markings? • How do AVs respond to non-traditional highway users (including farm implements and other agricultural uses)? • Do investment levels need to be varied based on geographic locations? For example, if operating an AV in a rural area and/or on a low volume roadway, does the infrastructure investment vary? • Should rules of operation vary in accordance with the level of roadside infrastructure technology?	*None*

6 Appendix

A. Definition of Terms

ADA	Americans with Disabilities Act
ADS	Automated Driving System
AV	Automated Vehicle
EV	Electric Vehicle
FTA	Federal Transit Administration
HAV	Highly Automated Vehicle
LSAV	Low-Speed Automated Vehicle
MaaS	Mobility as a Service
NHTSA	National Highway Traffic Safety Administration
ODD	Operational Design Domain
OEDR	Object and Event Detection and Response
SAE	Society of Automotive Engineers
TNC	Transportation Network Company
USDOT	US Department of Transportation
VMT	Vehicle Miles Traveled

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