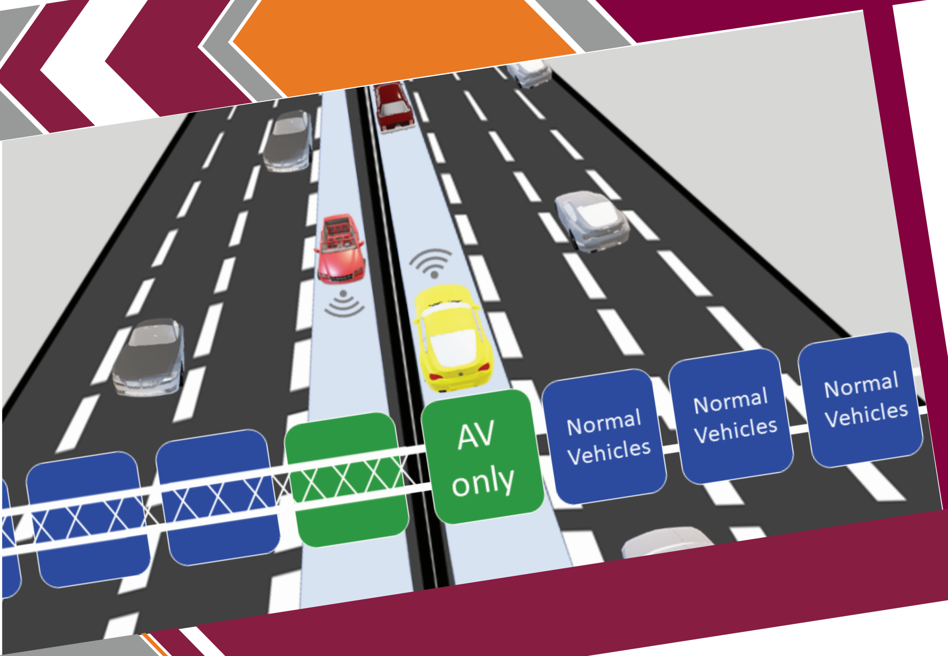
Safety Impact Evaluation of a Narrow Automated Vehicle-Exclusive Reversible Lane on an Existing Smart Freeway

February 2021 | Final Report



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Abstract

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Introduction and Background

The purpose of this study is to expand the knowledge base in terms of safety and operational impacts of exclusive freeway lanes for automated vehicles (AVs), and to investigate the implications of including a narrow AV-exclusive reversible lane on I-15 in San Diego County, California as a case study. The Interstate 15 (I-15) Express Lanes (EL) Corridor, between State Route 163 (SR-163) and Via Rancho Parkway, currently provide 4 HOV and toll-paying FasTrak lanes divided by a moveable barrier that allows reversible operation to accommodate peak hour movements. The lane combinations that can be provided, depending on peak direction and position of the moveable barrier that separates the northbound (NB) and southbound (SB) EL traffic, are 2 NB and 2 SB, or 1 NB and 3 SB, or 3 NB and 1 SB (see Figure 7 in Appendix A). Caltrans is seeking efficient ways to handle more traffic in the ELs, especially during rush hours or during major incidents when ELs are open to all traffic. In the available width between the fixed concrete barriers that separate the EL facility from the regular lanes, it would be possible to add a narrow reversible lane to be used only by AVs. This reversible AV lane for travel in the peak traffic direction would be 9 feet wide and located next to the moveable barrier. In both the NB and SB directions of the EL, there would be two 12-foot wide lanes for HOV and FasTrak vehicles and the outside shoulder next to the fixed barrier would be 8 feet wide (see Figure 8 in Appendix A). Considering this new configuration, we explore the traffic implications and considerations of AV lanes and whether AVs could operate safely in a 9-foot lane.

AVs are dependent on several sensors to recognize the surrounding environment and navigate the roadway. A road map is formed using the inputs from these various sensors, including ultrasonic, radar, imaging, and LiDAR sensors, allowing the vehicle to stay in the lane and adjust the control features for proper driving actions. Therefore, the operational features and logic of AVs are different from human-driven vehicles where operational decisions are made based on driver capabilities and behavioral characteristics. AVs' lane-keeping capabilities could allow for infrastructure standard adjustments, such as narrower lanes, fewer lanes, and smaller and less signage, which could result in more efficient mobility.

A full infrastructure adaptation will not take place quickly, especially given that the transportation system will be serving both AVs and human-driven vehicles for quite some time. Therefore, a mix of dedicated AV lanes and normal vehicle lanes seems to be a viable solution. Opportunities for dedicated AV lanes within regular lanes should be sought wherever possible to make a smoother transition to an AV-capable roadway system.

This research will shed light on the barriers AVs might face and benefits they could have on the existing infrastructure as well as the safety implications of infrastructure adaptation to AV technology. A series of tasks was completed, including a literature review, determining existing lateral control systems in AVs, collecting experts' and consumers' opinions on the study subject, and conducting crash data and traffic simulation analysis on I-15 ELs. The rest of this report details these tasks and provides recommendations and guidelines for narrow AV-exclusive lane development.

Literature Review

Existing Lateral Control Systems in AVs

Lateral control is what keeps a vehicle in a lane. Lateral control technologies have developed progressively, evolving from lane departure warning systems to lateral assist systems to lane centering systems. A comprehensive literature review was prepared considering existing research in the development of AV environmental perception technologies as it relates to lateral control, and current literature examining recommendations of infrastructure improvements to support AVs (see Appendix B).

Additionally, a review of 15 different vehicle manufacturers' existing AV technologies related to lateral control systems is presented in Appendix C. The vast majority of the vehicles reviewed incorporated some form of AV technology that placed them in SAE International's definition of AV levels 2–3 (*1*). A few manufacturers, such as WAYMO and Toyota, are developing level 4 and 5 vehicles. The review of vehicles is limited in scope to information available in the public domain (i.e., manufacturer websites, journal publications, and manuals). The review represents the major AV developers between the years 2014 to mid-2019. This review is intended to provide readers with an assessment of the general state of AV capabilities on the market at the time of this review's writing (June 2019).

AV capabilities will continue to develop and be refined for the foreseeable future. Concomitantly, AV safety and performance in real-world conditions needs to be continuously evaluated. The majority of corporate AV testing is on surface streets in urban areas. As most streets and freeways in the United States are designed to be 12 feet wide, AVs are trained and built for these conditions, and thus their performance in narrow lanes (<10 feet) may be unknown. Few AV manufacturers/developers release lane keeping accuracy statistics, with the notable exception of WAYMO and Cadillac. Some vehicles with AV features have limitations to the efficacy of their sensing systems, such as the Hyundai, for which the lane sensing systems can only operate in lane widths of 10–15 feet (*2*). However, not all AV manufacturers specify these limitations. Companies who do report accuracy statistics typically employ GPS maps for navigation, where the vehicles follow a prescribed track, thus suggesting a potential best or recommended practice. Should narrow AV-exclusive lanes be developed, vehicle manufacturers should first test their vehicle's ability to operate in curvilinear narrow lane environments. Integration of AVs into the transportation ecosystem has thus far proven to be a gradual and evolutionary process. As AVs proliferate and their capabilities improve, AV-exclusive lanes may prove beneficial for the successful integration of AVs into the operating environment in a safe and systematic manner.

Lane Width

The research team also reviewed literature related to lane width. Almost all research on lane width is in reference to conventional vehicles rather than AVs. Reduced width lanes have been previously considered for their traffic calming effects or because of geographical restrictions or existing right of way realities. It is important to consider research on reduced lane widths in order to understand how it impacts road design in the present. Previous research in this area may additionally aide in the identification of safety considerations should AVs be deployed on reduced width lanes.

A substantial amount of research regarding reduced lane widths pertains to safety considerations. Sharma et al. (*3*) found that 10-foot lanes on higher speed (40–45 mph) roads had an ambiguous impact on safety, observing improvements in safety at some locations and reductions at others. Wider lanes tended to be safer at corner speed limit curves. Sharma et al. also posit that drivers were more careful while driving in high speed locales with narrower lanes, but that narrower lanes tended to be associated with a larger number of lane violations. Intersections with narrower lanes for both the left turn and through lanes were safer than intersections with a narrower left turn lane and regular through lane. With regard to accidents, Potts et al. (*4*) concluded that lanes narrower than 12 feet did not consistently increase crash frequencies. Therefore, lane design policies should remain flexible with regard to narrower lane widths. An examination of roads from Minnesota and North Carolina showed no consistent and statistically significant relationship between lane width and safety. Potts et al. still caution narrowing lanes to less than 12 feet.

Public agencies are very sensitive to the impact of roadway infrastructure modifications. These impacts are quantified in accident/crash modification factors (*5*). Gross et al. (*6*) researched the impact of shoulder/widths combinations on accident rates and developed corresponding crash modification factors. The authors found that reallocating lane and shoulder widths given a fixed total pavement width can be a cost-effective measure for reducing accidents on rural, two-lane undivided highways. Gross et al. posit that for narrow widths, slight reductions in crashes can be achieved by adding shoulder widths compared to lane widths, but only in low traffic scenarios. Lee et al. (*7*) developed a comprehensive safety model with accident modification factors. The authors found that, in general, shoulder widths have a more substantial impact on safety when the lane width is narrow. The study also indicated that accident modification factors increase with decreasing lane or shoulder width.

It is important to also consider the functional impacts of lane width reduction, especially in regards to flow, speed, and level of service. A Federal Highway Administration research initiative (*8*) noted that the 1985 Highway Capacity Manual found that a roadway with 9-foot lanes and no shoulders could only support two-thirds of the capacity of a two-lane roadway with 12-foot lanes and 6-foot shoulders. The report found no flow benefits in reducing lanes to 10 feet or 9 feet. Rosey et al. (*9*) compared simulator derived data to a previous field study on the impact of lane width reduction on speed. The researchers found that simulator results corroborated previous field study findings on speeds, which indicated that speeds remained unaffected by lane narrowing, However, drivers tended to move towards the centerline after narrowing occurred and moved to the right (outside edge of lane) prior to meeting an oncoming vehicle. Dorothy and Thieken (*10*) explore the relationship between a number of different highway design variables, such as speed, level of service, physical characteristics of the design vehicle, and capabilities of the driver. In reference to lane width, the authors consider the recommendations of the 2004 edition of the Greenbook (*11*): "9-foot lanes are appropriate on low volume roads in rural and residential areas, or in urban areas, inside lane to accommodate wider shared use outside lanes." It is important to note that the aforementioned considerations are all heavily linked to human factors, and may be null and void in AV-exclusive lane scenarios.

It should also be noted that there is another challenge associated with introducing AV-exclusive lanes, especially narrow ones. Because AVs are programmed to follow a set path with minimum lateral wandering, they may have an unintended and unfavorable impact on pavement life and roadway hydroplaning. This aspect has caught researchers' attention recently, resulting in solutions such as proposing an optimal AV lateral wandering pattern (*12*).

Experts' Opinions on AV-Exclusive Lanes

A key task of the project was to survey and explore relevant academic researchers', transportation officials', and industry leaders' attitudes and opinions on the topic of AV-exclusive lanes. Given the rapid advancement of AV technology and the challenges of integrating AVs into the existing transportation network, these perspectives from experts are invaluable for decision makers to consider. A comprehensive questionnaire was developed, with questions ranging from identifying the value of the project as conceived and engineering and safety considerations of narrow lanes to public perception and engagement strategies and considerations. The survey was sent out to several experts; 17 responses were completed and sent back to the research team. The questionnaire was designed for two groups of (1) academia and transportation officials and (2) manufacturers/technologists. Out of 17 responses, 14 were provided by the first group and 3 by the second. Some of the questions were the same for both groups. The questionnaires are provided in Appendix D.

Several survey questions pertained to the feasibility and the value of the proposed configuration of the 9-foot AV-exclusive lanes. In general, most respondents (≈ 70%) were positive about the exclusive AV lane concept on the I-15 corridor, citing several advantages, including improving lane capacity and throughput, reducing congestion, improving road safety, increasing efficiency, helping demonstrate the viability of AV technology and therefore widening its public acceptance, and environmental benefits due to reduced emissions and fuel economy. Many surveyed recognized the technical and political challenges of integrating AVs into the existing transportation network. Some respondents (≈ 30%) expressed major reservations with the concept because an exclusive AV lane in the middle of I-15 could potentially lead to confusion among non-AV drivers and create conflict points during an AV's entry or exit. Many questioned the perceived advantages of an exclusive AV lane in low market penetration conditions, citing low capacity and efficiency, high cost, and potential increase in congestion in non-AV lanes. Some respondents asserted that exclusive AV lanes could create safety issues due to the inability of most AVs to take evasive actions and due to the absence of a concrete barrier between AV and non-AV lanes. Some others believed that exclusive AV lanes could create equity issues, especially in low market penetration conditions because of the perceived favorable road access to wealthy people who could afford AVs.

The next few questions placed a major emphasis on AV operation safety. Some of the safety issues were related to the limitations and uncertainties associated with AV environmental sensor technology. Many respondents expressed concern over the reliability, accuracy, and communication latency of AV sensor operation and strongly expressed the need for clear markers and signage for proper AV sensor operation at all times of the day and night. Some cited uncertainties arising from the low margin of error on a 9-foot lane, while others cited compatibility issues for sensors that were calibrated to operate on 12-foot lanes. Many experts also raised concerns regarding adverse weather conditions as a major limitation that may hamper proper sensor operation and thus may affect safety. Adverse weather conditions have the potential to negatively impact key navigation systems, such as optical camera systems. In addition, poor weather conditions can also affect the pavement marking retroreflectivity performance. Most of the respondents showed similar or stronger concerns with respect to the impact of wind gusts/snow/ice/fog on AVs' lateral control function. Vehicles pushed away by heavy wind gusts, pavement markings covered due to snow/ice, and decreased visibility due to fog are some of the negative impacts of adverse weather condition concerns expressed by the experts. To mitigate these issues, they suggested several solutions, including improved striping: 6-inch lines and dashed striping through gore and ramp areas according to The National Committee on Uniform Traffic Control Devices (NCUTCD), installing wet reflective markings that aid machine vision systems to improve performance (especially during nighttime), and providing physical barriers on both sides.

The survey then explored several questions related to AV lane infrastructure, as it plays an important role in the success of the exclusive AV lane project. Respondents listed few limitations associated with roadway geometry and provided insights on the solutions to those limitations. Vehicle dynamics around curves on the narrow lane were one such limitation, as sensors can also have line of sight issues around curves. This is particularly problematic if there is a queue of vehicles on the other end of the curve, which might require the AV to brake suddenly. Respondents suggested solutions like standardizing the geometries and speed limits, allowing only regular-weight vehicles, and widening the lanes around curves. In addition, special restrictions for heavy AVs on narrow lanes were also suggested by the experts due to issues related to the bulkiness of heavy AVs, proximity to non-AVs, turning radius, and GPS accuracy. Some of the supporting infrastructure that many respondents strongly agreed on incorporating were highly reflective, clearly visible and distinct lane markings, concrete barrier sensors, and the inclusion of roadside units that update restrictions in real-time. However, most respondents were of the opinion that the exclusive AV lane would still be impacted by infrastructure non-idealities like potholes and non-uniform lane markings.

The next few questions explored the regulatory efforts related to AV autonomy and market penetration. When asked about what minimum level of autonomy would be sufficient for AVs to be safely allowed in the exclusive lane, there was no clear consensus among the respondents; however, the responses leaned toward the notion that the higher the level of autonomy (level 3 and up), the better. Most respondents were not aware of any ongoing regulatory efforts to existing vehicle standards or transportation design manuals but some of them suggested the need for credible bodies like the National Highway Traffic Safety and Administration (NHTSA) and NCUTCD to approve AV safety, provide guidelines about AV lane infrastructure, and provide code to prevent non-AVs from entering the AV lane. Most respondents believed a 10% to 30% market penetration rate (MPR) would be sufficient to make an AV lane viable, and that an MPR over 50% could warrant decommissioning of AV lanes.

A few specific questions were targeted at academic and transportation officials pertaining to safety concerns associated with implementing narrow 9-foot lanes, the effect of an AV exclusive lane on the efficiency of traffic flow characteristics and capacity of existing general purpose lanes (GPLs), and, finally, efforts to spread awareness.

Addressing the question related to safety concerns associated with implementing narrow 9-foot lanes, several respondents cited concerns about how and when AVs would enter and exit the AV exclusive lanes. Some thought AVs exiting the exclusive lanes at high speeds and entering into GPLs may pose safety concerns. In addition, a major concern expressed by the respondents was that high-speed AVs next to potentially slow conventional vehicles could encourage those vehicles to violate rules and enter AV exclusive lane, especially in congested GPLs conditions. Another key safety concern identified by several experts was the nature of the narrow lanes; 9-foot lanes compared to the traditional 12-foot lanes will have diminished maneuver space in the event of unforeseen obstacles or unsafe maneuvers by other drivers.

Addressing the questions related to the effects of the narrow 9-foot AV lane on the efficiency of traffic flow characteristics and capacity of existing GPLs, most respondents asserted that there would be an improvement in overall traffic flow with AVs in their own lanes with tighter headways, but there would be disruptions in the traffic flow due to AVs merging in and out of the 9-foot lane. While some believed that 9-foot AV lanes with connected and automated vehicles could greatly improve efficiency, others believed that such an arrangement could create uncertainty among human drivers adjacent to AV lanes.

For the effect of an AV lane on the capacity of existing GPLs, while many respondents thought that capacity might improve due to platooning, some again pointed out the disruptions that could be created due to merging and weaving may cause a negative impact on the GPL capacity. While some experts expressed concerns about reduced lane capacity due to slow-down of conventional vehicles as a result of their close proximity of AVs, others believed that capacity would remain unchanged.

The survey also explored the education and training of new AV lane users. Many surveyed emphasized the importance of early education and training at the driver's license level. Most believed that extensive public outreach via internet, social media, and other campaigns would also be necessary to explain how the lanes should be used or not used by non-AV drivers.

The final set of questions, related to AV technology and its effectiveness, were targeted at manufacturers/technologists and few key insights were gained. For safe travel of AVs during nighttime, experts advised precaution with respect to wet pavement surface reflectivity and expressed concerns about vision-based systems, which are vulnerable to low light conditions. Regarding a speed limit for AVs, experts were of the opinion that no specific speed limit could be set at present, as limits will depend on other factors, such as vehicle connectivity and weather conditions. When questioned if modified white lane markings enhanced with black stripes could aid AVs in lateral control function, there were no strong conclusions drawn, though concerns were expressed about uniformity in striping and being region specific. As to the impact of environmental stressors, such as lane splitting and aggressive human drivers, on an AV's response, experts assumed that under such situations AVs would not veer but would come to a stop as an immediate response.

When asked about the need for remedial component redundancies to be available in AVs to prevent catastrophic incidents due to failure in the lateral control-related AV system, experts answered that most probably no remedial component redundancies are currently available. They also added that though there are automotive safety integrity level requirements for AVs, currently there are no requirements for redundant control systems. For questions regarding sensor thresholds for safe AV operation, minimum AV lane width requirement, and codification and measurement of lane keep system accuracy, no responses were received.

Overall, most of the respondents saw the merit of AV-exclusive lanes. Many voiced their concerns about the safety aspects of the proposed configuration, and brought insight into some unforeseen challenges of the concept.

Consumers' Opinions on AVs' Lateral Control Systems

AV-exclusive lane design would greatly benefit from a firm understanding of the limitations of current AV technology. Consumer complaint data could serve as a relatively reliable representative of AV limitations, as complaints reflect real-world experiences with the technology. This study utilized information from NHTSA's Vehicle Owner Questionnaires database (*13*) to evaluate safety issues that consumers have encountered related to lateral vehicle control technology in AVs. The complaints from the consumer database were extracted based on specific keywords as well as the vehicle's make, model, and year. The keywords used in the search were lane, center, centering, keep, keeping, ping pong, position, positioning, ALC (automated lane centering), LKAS (lane keep assist systems), width, marking, steer, line, shaking, camera, vibrating, and assist. Out of these initial keywords, 10 were selected as the final set of keywords: lane, keep, steer, position, center, line, shaking, camera, vibrating, and LKAs. The remaining terms did not return any results. The data were considered for all AVs manufactured between 2014 to 2019, as these vehicles were potentially equipped with the automated lateral vehicle control technology. The extracted data were then repurposed in Excel spreadsheets for detailed analysis.

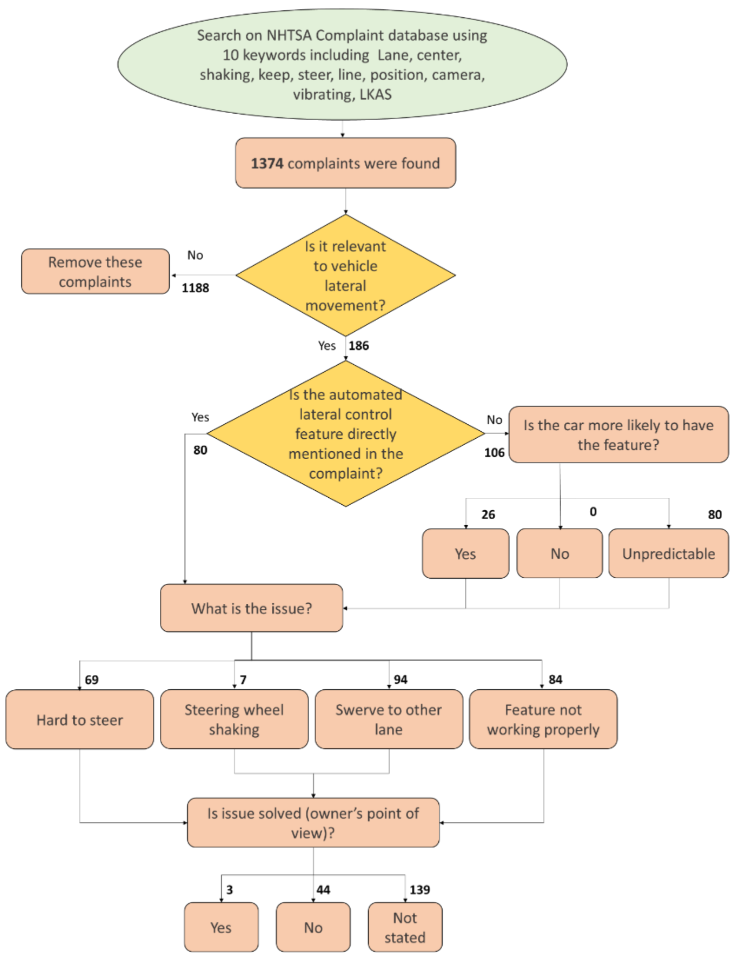

Figure 1. Flowchart of NHTSA Complaint Database analysis.

Figure 1 shows the flowchart for the complaint analysis process. A total of 1,374 complaints were found. These were then filtered into relevant—associated with the AV lateral movement—(count: 186) and irrelevant (count: 1188) complaints. The irrelevant complaints were discarded from further analysis. Of all complaints, 31% stated that the AV related issues occurred when the car was on a highway, 10% of the complaints stated they occurred on a road type other than the highway, and the remaining 59% did not state the road type. In Figure 2a, the number of times each keyword was associated with the complaints is illustrated in percentage. In some cases, more than one keyword was associated with a relevant complaint. The keywords "lane" and "steer" constituted the majority of the keywords, appearing 124 times (33%) and 111 times (30%), respectively.

Of all the complaints, 43% (count: 80) directly mentioned the AV feature, while 57% (count: 106) did not. In the latter group of complaints, 24.5% (count: 26) were more likely to have the AV feature (based on the vehicle make, model, and year).

The complaints were read thoroughly and further categorized into four different lateral movement related issues: "hard to steer," "steering wheel shaking," "swerve to other lane," and "feature not working properly." It was also found that more than half (57%) of the complaints were recurring while 35% of the complaints occurred only once. Finally, four categorized lateral movement related issues were scrutinized to find out if the issues were resolved from the owner's point of view, and it was found that 1% of the complaints were resolved, 24% of the complaints remained unresolved, and the remaining complaints (75%) did not state whether the issue was resolved or not.

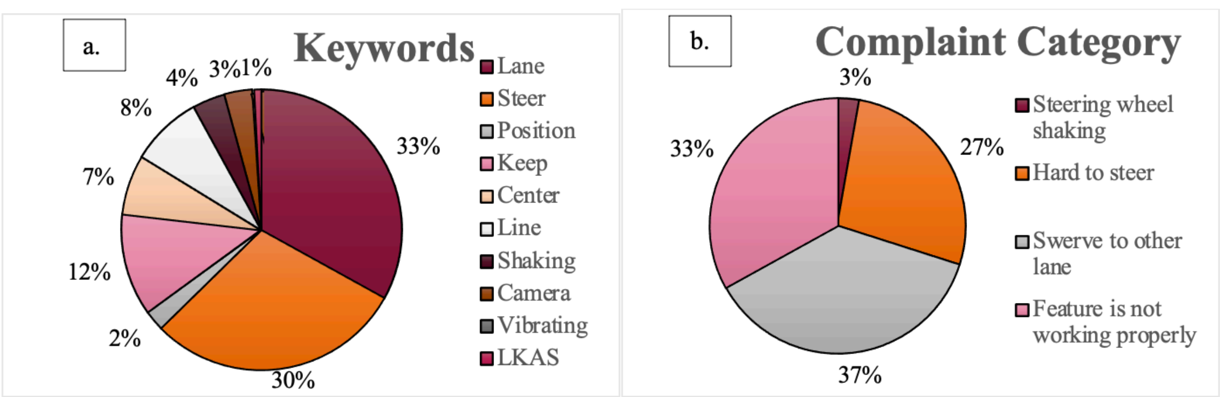

Figure 2. a) Frequency of keywords in complaints, b) complaint category.

Figure 2b is a pie chart of complaint category (type of lateral movement issue), which shows that the majority of the complaints indicated "swerve to other lane" (37%) as the issue. Swerving can lead to severe crashes with vehicles in adjacent lanes. Exclusive AV lanes with physical barriers on both sides could prevent crashes with vehicles in adjacent lanes. However, a collision with the barrier itself might occur, resulting in interruption of AV-exclusive lane traffic flow, especially if only one AV lane exists with physical barriers on both sides. "Feature not working properly" (33%) was the second major issue reported by the consumers, which could result in flow interruption and even crashes in the AV-exclusive lane. High reflective, clearly visible, and distinct markings and signage could support proper AV sensors and features operation. It is highly imperative to design an AV system (including both vehicle and infrastructure) that is robust in all conditions to ensure a high level of safety and mobility in the exclusive AV lane.

Investigation of I-15 Express Lanes Crash History

Crash data provide important information, such as type, severity, and potential cause of crash, and could illuminate potential shortcomings of operating AVs on the I-15. Historical crash data on the I-15 ELs were examined. The primary source of data for conventional accident information was the California Highway Patrol's Statewide Integrated Traffic Records System database. Data were selected based on location, jurisdiction, and year. Ten years (2009–2018) of data were collected for the I-15 corridor, which included three CSV files: collision data, party data, and victim data. The three files were combined based on the same incident number in each of these files. Each incident number was sometimes observed to have multiple vehicles or injuries/fatalities associated with it. In this study, all the vehicles involved in a particular incident were considered in the analysis. Roadway shapefiles from Caltrans were used to filter only those data points (i.e., crash locations) that were in the designated area of interest (I-15 ELs from SR 52 to SR 78). The filtered data points with their associated attributes were exported and used for further analysis. A total of 717 incidents were observed from 2009–2018 at the study site. When considering all vehicles involved in each incident, 1,473 crashes were analyzed. Some of the attributes considered in this study include primary collision factor, type of collision, and collision severity.

Primary Collision Factor, Type of Collision, and Collision Severity

Primary collision factor (PCF) consists of a number of different violation categories that were determined to be the main reason for a crash, as shown in Figure 3a for I-15 ELs crash data. To further understand the specifics of a crash, type of collision and collision severity were analyzed in conjunction with the PCF (Figure 3a, b, and c). In the PCF graph, more than half of all crashes were due to unsafe speed (55%, count: 814 crashes), 19% (count: 279 crashes) were due to improper turning and 13% (count: 196 crashes) were due to unsafe lane change. From the type of collision graph, it was observed that rear-end collision dominated the list, accounting for 55% (814 crashes) of all crashes recorded, followed by side-swipe (22% each, 317 crashes) and hit-object (16%, 234 crashes). In the collision severity graph, although there were very few cases of fatality (0.5%, 8 fatalities), many human injuries were reported, ranging from complaint of pain to severe injury (36%). Property damages accounted for 36% of the crash consequences and 27% were no injury cases. It should be noted that in this study, every vehicle involved in the incident was mapped to the highest degree of collision severity experienced by any of the passengers.

The research team also investigated the three crash attributes for non-ideal environmental conditions, such as adverse weather conditions (see Appendix E). The results showed the same set of PCFs, collision types, and severities were dominant in causing a majority of the crashes.

Interaction of Top Three Primary Collision Factors With Type of Collision and Collision Severity

The three main PCFs were further analyzed in combination with Type of Collision and Collision Severity to sketch the crash cause, effect, and consequence relationship (see Figure 4).

Unsafe speed is the most important PCF, contributing to around 55% of the total crashes. As Figure 4 shows, most crashes involved rear end collisions and accounted for 87.1% of total unsafe speed crashes (count: 709 crashes). Among these crashes, human injuries, ranging from complaint of pain to severe injury, and property damage were estimated to be 33% and 34% respectively. However, no fatalities were observed. The second and third highest categories were hit object (6.1% of total unsafe speed crashes, count: 50 crashes) and sideswipe (4.2% of total unsafe speed crashes, count: 34 crashes) collisions. Of the total three fatalities, hit object, broadside, and sideswipe collisions accounted for one fatality each.

Crashes caused due to unsafe speed can potentially be reduced with the use of AVs. AVs follow speed protocols with less variability and maintain close to accurate bumper to bumper spacing, provided the performance of environmental sensors are accurate and reliable. Even if one or more sensors fail, there should be sufficient redundancies in the system to mitigate performance degradation significantly. Previous research has also shown the safety benefits of AVs in reducing this type of collision. For example, Najm et al. (*14*) reported that automotive collision avoidance systems (e.g., forward collision warning and adaptive cruise control) can potentially prevent 6–15% of crashes.

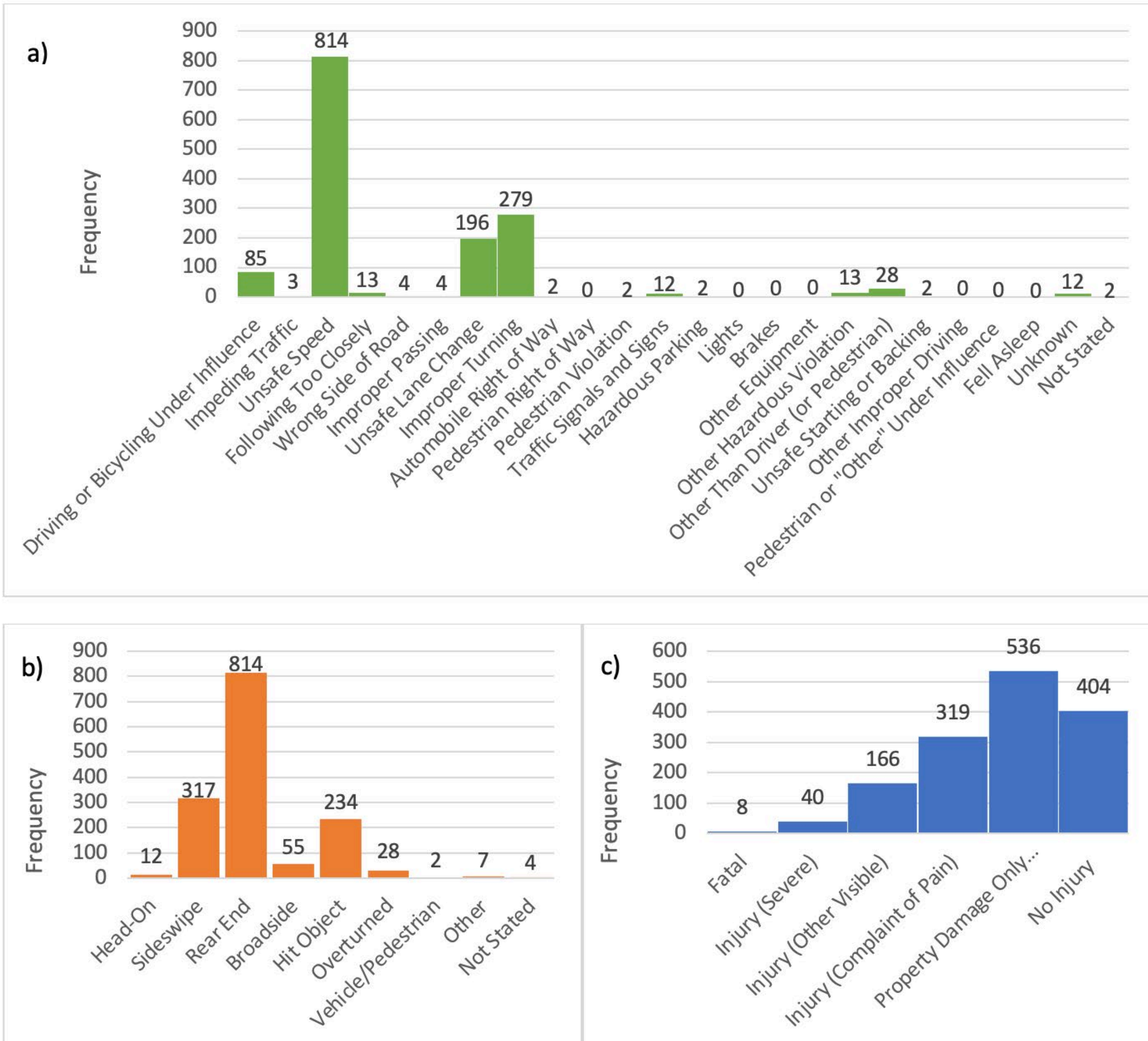

Figure 3. a) Primary collision factor (PCF), b) collision type, c) collision severity.

The next PCF analyzed was improper turning, which contributed to around 19% of total crashes on I-15 ELs. Hit object collisions (41.9% of total improper turning crashes, count: 117 crashes) in this category mostly resulted in property damage and human injuries ranging from complaint of pain to severe injury. There was also one fatality in this category. The second highest collision type was side-swipe (38.3% of total improper turning crashes, count: 107 crashes) with collision severity ranging from complaint of pain to severe human injuries and property damage. Besides hit-object and sideswipe, a small number of rear-end (8% of total improper turning crashes, count: 22 crashes), over-turned (4% of total improper turning crashes, count: 10 crashes), and broadside collisions (6% of total improper turning crashes, count:16 crashes) were observed.

AV attributes such as LKA systems have the capability to prevent the vehicle from drifting from its desired path, thus avoiding improper turning. Additionally, lane infrastructure needs to be designed carefully, such that the barrier/median is detected and interpreted by the AV sensors correctly with little room for error. Well-designed and functioning environmental sensors, signboards, and markings are required for safe travel of AVs in an AV-exclusive lane. However, AVs are susceptible to turning errors when the weather conditions are adverse or if the appropriate sensors fail, and caution should therefore be exercised when designing the AV and the AV-exclusive lane to promote proper turning at all times.

The next important PCF observed on I-15 EL was unsafe lane changes, which accounted for 13% of total crashes on I-15 ELs. Crashes due to unsafe lane changes resulted mainly in side swipe collisions (72% of total unsafe lane change crashes, count: 142 crashes) causing property damage and human injuries ranging from complaint of pain to visible injury. A few unsafe lane change incidents resulted in rear-end and broadside collisions (10% and 5% of total unsafe lane change crashes, count: 20 and 10 crashes, respectively), which caused property damage and human injuries ranging from complaint of pain to visible injury. Hit object and overturned collisions caused property damage and human injuries ranging from complaint of pain to severe injury. No fatality incidents were observed during unsafe lane change incidents.

AV attributes such as lane departure warning systems (LDW), LKA systems and lane centering can help to reduce unsafe lane departures, leading to safer travels on ELs. As mentioned, caution should be exercised when designing AVs and AV-exclusive lane to avoid unsafe lane changes due to adverse weather conditions and/or sensor failure. Restricted access to AV-exclusive lanes from GPLs can also prevent unsafe lane changes. The points of access from/to the AV-exclusive lane to/from a GPL need to be carefully designed and monitored. Considering proper infrastructure design at these access points will prevent crashes due to unsafe lane departures as well as improper turning.

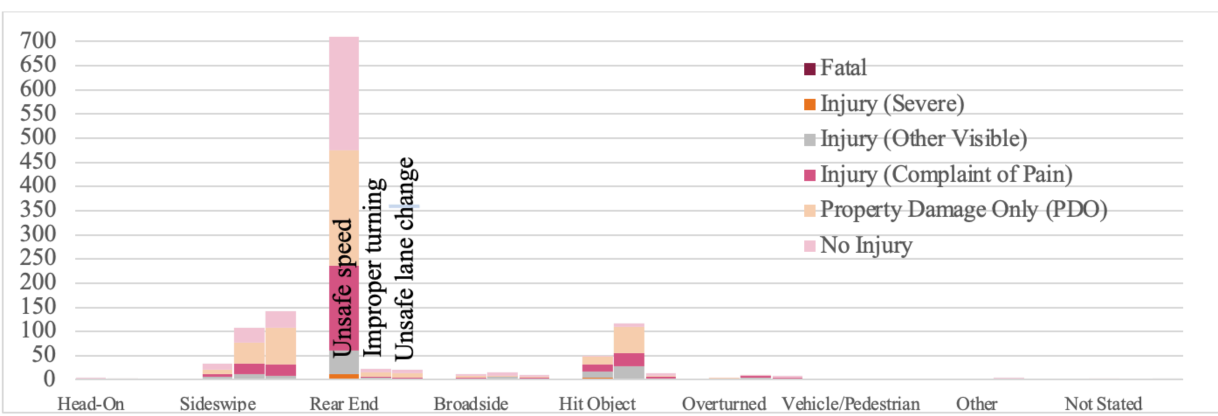

Figure 4. Types of collisions for different collision severities attributed to three main PCFs.

Impacts Analysis Using Microsimulation

Technical Approach

Microsimulation was used to evaluate the impact of implementing the proposed AV-exclusive lane on the I-15 ELs. To best understand the project's effect on transportation, a sensitivity analysis was conducted for three scenarios as noted below. The microsimulation model was developed with the Caliper TransModeler SE version 5.0 software package. The following sections will discuss in more detail the microsimulation input assumptions and output metrics used for the evaluation.

Scenario 1 – EX:	Baseline/calibration scenario with existing volumes/network
Scenario 2 – AV:	Existing volumes/network with AV adoption
Scenario 3 – AVL:	Existing volumes with proposed AV exclusive lane and adoption

Corridor Network

The microsimulation evaluated a section of the I-15 ELs corridor, approximately 7 miles in length, between Ted Williams Freeway (State Route 56) to State Route 163. The ELs were modeled in the simulation environment, including all physical features such as merging and diverging points, acceleration/deceleration lanes, Direct Access Ramps, and lane/shoulder configurations and width. Figure 5a and Figure 5b illustrate the extent and configuration of the network. The network was divided into 12 segments as numbered on the figure. The microsimulation outputs were collected in the middle of each segment on an individual lane basis.

Figure 5c illustrates the lane configuration under scenario 3 for the SB direction during the a.m. peak hour. The morning peak hour scenario was selected since it is the most conservative period given a more critical traffic condition occurs during the morning in comparison to the evening peak hour.

Input Assumptions

In addition to physical features of the network, microsimulation parameters were modified to reflect the field conditions. Heavy vehicles were not modeled, with the assumption that they are not permitted on the ELs. Non-AVs were evaluated with the Modified General Motors Car-Following Model which is the default setting of the software. Per the software developer's guidance, AVs were evaluated with the Constant Time Gap Car-Following Model.

Under scenarios 2 and 3, AVs were modeled with automation level 3 - conditional automation. Levels 1 and 2 automation were not considered, given they represent driver support rather than true vehicle automation. Under scenarios 1 and 2, AVs were assumed to have the same deviation from the speed limit as non-AVs. This assumes approximately 30% of drivers were traveling within the speed limit. Under scenario 3, level-3 AVs were not affected by non-AVs as they were traveling in the AV-exclusive lane. Therefore, the AVs were assumed to travel at the speed limit.

The AV MPR for the baseline scenario was assumed to be zero since level 3 AVs are not currently available. Scenarios 2 and 3 assumed varying level 3 MPRs of 15%, 30%, and 45%. This approach provided sensitivity to the analysis given that it is difficult to predict MPR with certainty.

Each microsimulation was run for 60 minutes using the peak hour volumes. A maximum warmup period of 10 minutes was also assumed to preload the network.

Baseline Volumes

Baseline volumes and speeds were received from Caltrans. The extracted data represents morning peak hour (7 a.m.–8 a.m.) volumes and speeds on HOV lanes from Tuesday October 15, 2019 to Thursday October 17, 2019.

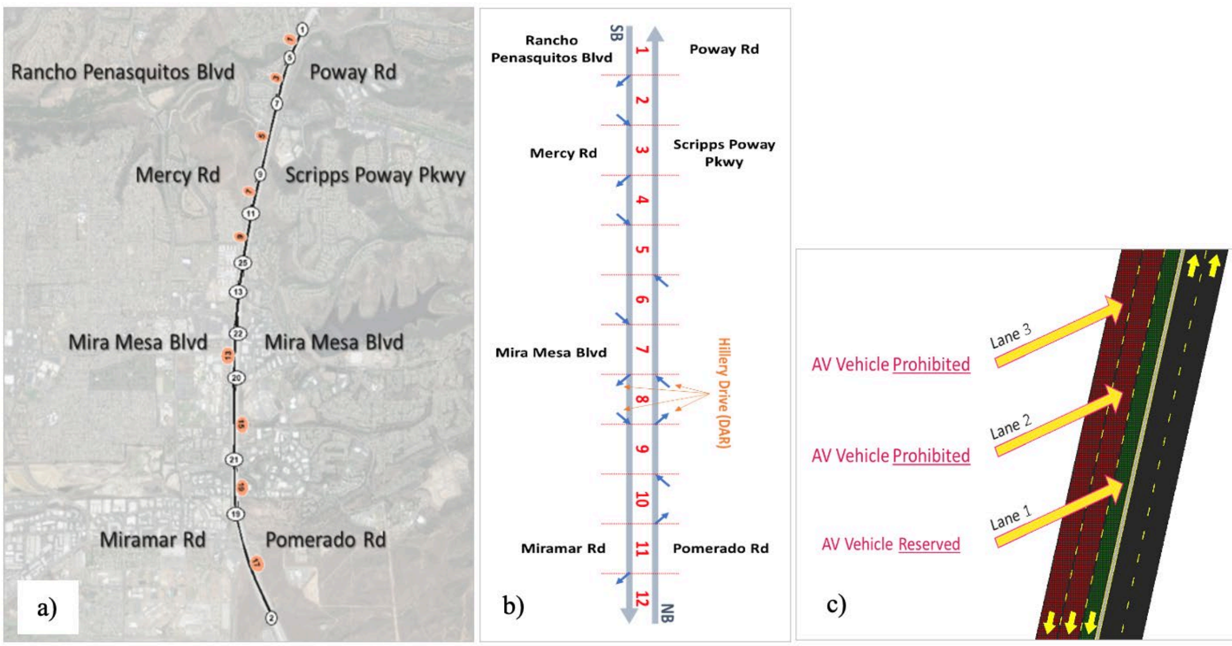

Figure 5. a) Network extents, b) network features, c) a sample of the road in scenario 3.

Calibration

Existing field volumes were inputted into the software to verify that the microsimulation accurately represented field conditions. Volumes, in veh/hr, and speeds, in mph, yielded from the model were then compared to available field data. In addition, the Geoffery E. Havers (GEH) value was used for the calibration process and to assess how the microsimulation outputs matched the field conditions. A Low GEH, under five, indicates a well calibrated model. An average GEH of 0.40 and 0.77 was achieved for the NB and SB directions, respectively (see Table 1).

a) b) c)

Table 1. Simulation calibration

#	Location	Dir	Field Data: Volume*	Field Data: Average Speed	Simulation Output: Volume	Simulation Output: Average Speed	Δ Volume	Δ Average Speed	GEH
1	Rancho Penasquitos Blvd / Poway Rd	NB	800	71.3	775	71.7	-3%	1%	0.89
		SB	3500	75.9	3499	72.5	0%	-4%	0.02
2	Mercy Rd/ Scripps Poway Pkwy	NB	700	66.2	689	70.7	-2%	7%	0.41
		SB	2500	75.5	2474	70.5	-1%	-7%	0.52
3	Mira Mesa Blvd	NB	800	69.0	792	73.0	-1%	6%	0.29
		SB	3400	71.9	3340	70.3	-2%	-2%	1.04
4	Miramar Rd / Pomerado Rd	NB	800	73.6	800	76.5	0%	4%	0.00
		SB	3000	73.7	2917	70.2	-3%	-5%	1.52
						Average NB	***-1.4%***	***4.3%***	
						Average SB	***-1.4%***	***-4.6%***	

** Field volumes are rounded to nearest hundred*

Results

The microsimulation results were reviewed under four selected metrics: traffic flow, average density, average speed, and speed differential.

Traffic Flow

Traffic flow data, in veh/hr, for all lanes were collected on each segment of the network. Appendix F shows, in more detail, the percent change in the flow of traffic on each segment compared to scenario 1 (baseline scenario). Under scenario 2, the introduction of level 3 AVs into the existing network did not show any measurable change in traffic flow. Under scenario 3, however, the introduction of level 3 AVs on an AV-exclusive lane resulted in up to a 14% increase in traffic flow depending on the corridor location and AV MPR.

Average Density

Average density was calculated for the length of the segment in vehicles per mile per lane. Figure 6 demonstrates average density along the corridor. Similar to traffic flow, changes in average density were insignificant in scenario 2. The average density of most segments was found to increase by up to 24% under scenario 3.

It should also be noted that in the 45% MPR scenario, a significant increase in density was observed on segment 10. It is suspected that this is related to the compound effect of an existing curve, high ramp volumes, and higher AV-exclusive lane saturation.

Average Speed

The average speed of each segment was also evaluated. Consistent with the traffic flow and density, under scenario 2, no measurable difference was observed on average speeds. Under scenario 3, the average speed declined by 2–8 mph depending on the location and AV MPR. The drop in speed was expected given the AVs were assumed to travel at the speed limit in the model. As indicated in the "input assumptions" section, this compares to only 30% of non-AVs and the AVs in scenario 2, which were assumed to travel at the speed limit.

Speed Differential

The speed differential between lanes 1 (adjacent to the left shoulder) and 2 were determined on each segment. It is important to note that under Scenario 2, lanes 1 and 2 had similar characteristics (i.e., ELs). Scenario 3 introduced a distinction between lane 1 (i.e., AV exclusive lane) and lane 2 (i.e., EL). Table 2 shows the speed differential range between the two scenarios. Appendix F includes additional graphs to show the speed differential between all three lanes.

Under scenario 2, speeds varied by 0.2 to 2.2 mph (absolute values). Under scenario 3, speeds varied by 1.9 to 14.3 mph (absolute values). A range of speed variations (e.g., 0.2 to 2.2 mph in scenario 2) was due to the differences between segments and MPRs. Lowest speeds on dedicated AV lanes were observed at segment 10, where the highest density, low traffic flow and low average speeds were recorded as well.

Previous studies have suggested that a high speed differential, for example, between HOV lanes and GPLs may warrant the installation of barriers between the two lanes (*15*) (*16*). The studies suggest that non-AV drivers may feel more comfortable driving with a maximum speed differential of no more than 15 mph between lanes. They also suggest that speed differentials between 10 to 15 mph, while not warranting physical separation, may benefit from a buffer, such as double line markings, separating the lanes.

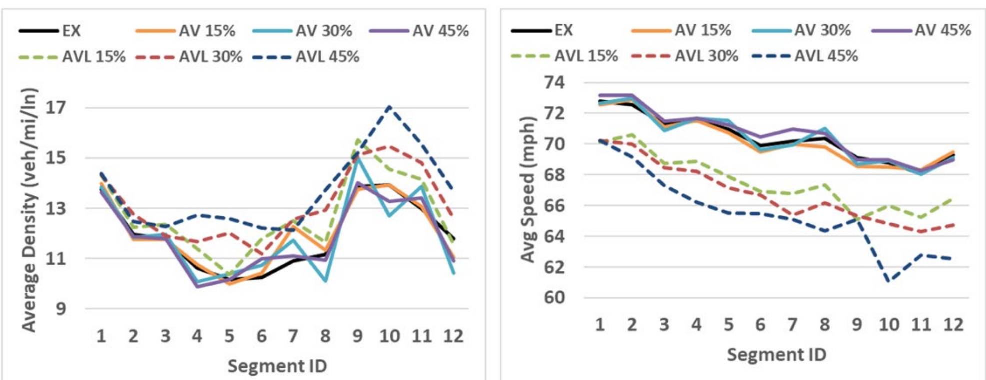

Figure 6. Average density and average speeds.

Table 2. Speed Differential Range (mph)

Range	**Scenario 1** EX	**Scenario 2** AV 15%	**Scenario 2** AV 30%	**Scenario 2** AV 45%	**Scenario 3** AVL 15%	**Scenario 3** AVL 30%	**Scenario 3** AVL 45%
Lower range	-0.7	-1.9	-2.2	-1.4	-6.0	-9.4	-14.3
Upper range	1.4	0.2	0.4	0.9	-1.9	-4.8	-6.6

Key Microsimulation Findings

From a corridor capacity perspective, at level-3 automation, an AV-exclusive lane provides substantial benefits. Traffic flow was observed to increase by up to 14% depending on the corridor location and AV MPR. Similarly, density was observed to increase by up to 24%. This can be attributed to the lower vehicle headways and more stable flows afforded by AVs. The additional capacity can be attributed to changes in AV driving dynamics and technology as opposed to an addition of a lane. It should be noted that the additional lane in scenario 3 was added in the NB direction and did not impact the result of the southbound traffic analysis presented here.

From a safety perspective, adding an AV-exclusive lane does not reveal any significant flaws and shows potential benefits. Despite capacity and density increasing, the average speed was observed to be 2 to 8 mph lower depending on the location and AV MPR. In general, lower speeds can be associated with lower crash severity.

This study does reveal the importance of understanding the impact of changing roadway characteristics. Specifically, it shows the speed differential between lanes 1 (adjacent to the left shoulder) and 2. The AV-exclusive lane introduces a distinction between lane characteristics that will require careful consideration if additional treatments or barriers are required.

Furthermore, AV vehicles may provide additional safety benefits not quantified in the microsimulation models. AV have the potential to remove human error from the crash equation, the root cause of most accidents.

Conclusions and Recommendations

General Recommendations

1. Standardization of lane markings, signage, mapping of roads, speed limits, and geometries for AV operations on exclusive lanes are recommended across the nation, while still accounting for non-AV compatibility.
2. Highly reflective, clearly visible, and distinct lane markings and signage are required for proper AV sensor operation since reliability, accuracy, and communication latency in AV systems are critical.
    a. White lane markings surrounded by black paint could be effective.
    b. Improved striping, such as that suggested in the marking language by NCUTCD on gore and ramp areas that includes 8-inch lines and dashed striping, could enhance machine vision systems' performance in AVs.
    c. Wet reflective markings are recommended as they aid machine vision systems to improve their performance, especially during nighttime.
    d. Signage such as "Keep Lane Assist On" are recommended for all levels of automation, especially for lower levels of automation.

3. Same direction physical barriers between AV-exclusive and adjacent lanes are recommended to prevent crashes due to improper turning and swerving. Also, barriers with active sensors may aid in lateral control of AVs by providing clear physical signals continuously measured by AV sensors.
    a. Lane friction (difference in average speeds of AV-exclusive lane and adjacent lane) could be used to determine if barriers are warranted; there are recommendations indicating speeds ≥ 30 mph warrant physical barriers/separators; however, lane friction of 10-15mph does not warrant physical barriers/separators, but rather buffer separated double solid lines.
4. Nighttime restrictions should be considered, as vision-based sensor systems are vulnerable to low light conditions, especially in wet pavement conditions.
5. Infrastructure non-idealities, such as potholes, non-uniform lane markings, etc., should be minimized, as AVs are vulnerable to these non-idealities.
6. Widening the lanes around curves is recommended, especially for a "narrow" AV-exclusive lane, as generally AVs are susceptible to turning errors (particularly in adverse weather conditions).
7. Operation of heavy AVs is challenging, especially for a "narrow" AV-exclusive lane, due to their bulkiness, proximity to non-AVs, turning radius, and GPS accuracy, and hence specific restrictions for heavy AVs should be developed.
8. To support safe operation of AVs, roadside units that facilitate vehicle to infrastructure (V2I) communications can be implemented to provide real time critical traffic information to AVs.
9. The access points from/to the AV-exclusive lane need to be carefully designed and monitored to prevent unsafe lane changes as well as manage traffic flow distribution on all freeway lanes.
10. Depending on traffic conditions and MPR, restrictions should be placed to designate the lane as AV-exclusive, shared with HOVs, or open to all traffic.
    a. There are expert recommendations suggesting that an MPR of 10% to 30% may be sufficient to make AV-exclusive lanes viable, and that an MPR over 50% may warrant decommissioning of AV-exclusive lanes.
11. AV application limitations should be taken into considerations.
    a. For example, some AV lateral control systems, such as lane departure warning systems, are effective above certain speeds (e.g., 30 mph, 38 mph, and 44 mph), are operational for certain speed range (e.g., 37 mph–112 mph or 40 mph–110mph), only work if lane width is between 10 and 15 feet, operate if only two lane markings are detected, and do not perform well in sharp turns, during low visibility, or in foul weather conditions.
    b. There are consumer reports of AV lateral system features not working properly or of AVs swerving into other lanes.
12. Early education and training at the driver's license level as well as extensive public outreach via internet, social media, and other campaigns are recommended to explain how the lanes should be used or not used by AV and non-AV drivers.

13. Simulation modeling with real-world traffic data (volume, MPR, etc.) specific to the candidate site could significantly aid in making informed decisions on feasibility, limitations, and specifications of AV-exclusive lanes.

Specific to I-15

1. According to crash data analysis, unsafe speed was the most recurring PCF on I-15 ELs. The majority of unsafe speed events resulted in rear end collisions. Implementation of an AV-exclusive lane could potentially reduce this type of crash, since AVs are expected to follow proper speed discipline with less variability and maintain sufficient bumper to bumper spacing.
2. Improper turning and unsafe lane change were the next two most recurring PCFs, the majority of which resulted in hit-object and sideswipe collisions. AVs' automated lateral control systems (e.g. LKA) could potentially reduce these collisions on an AV-exclusive lane. However, high reflective, clearly visible, and distinct lane markings, barriers, and signage are required for proper AV sensor operation. Also, the points of access from/to the AV-exclusive lanes need to be carefully designed and monitored.
3. Microsimulation findings indicated an AV-exclusive lane may increase traffic flow and density by up to 14% and 24%, respectively. This is achieved with lower vehicle headways and more stable flow afforded by AV driving dynamics and technology.
4. Microsimulation findings also indicated an AV-exclusive lane has better speed limit compliance and therefore average speed is reduced. The lower speed may contribute to lower crash severity. However, the study reveals the importance of understanding the impact of roadway characteristics. Specifically, the speed differential between the exclusive lane and adjacent lane should be considered. An AV-exclusive lane introduces a distinction between lane characteristics that may result in an increase in speed differential, which will require careful consideration if additional treatments or barriers are required.

Additional Products

Education and Workforce Development Products

- Three graduate students and one undergraduate had the opportunity to work on this project.
- The project industry partner, LLG, plans to present the study at local transportation professional organizations such as the Institute of Transportation Engineers (ITE).
- A teaching module was developed.

Technology Transfer Products

- **Published journal paper:** Ghanipoor Machiani, S., A. Ahmadi, W. Musial, A. Katthe, B. Melendez, & A. Jahangiri. (2021). "Implications of a Narrow Automated Vehicle Exclusive Lane on Interstate 15 Express Lanes." Journal of Advanced Transportation, Special Issue on “Traffic Safety in Intelligent and Connected Environment.” https://www.hindawi.com/journals/jat/2021/6617205/

- **Conference poster presentation:** Melendez, B., A. Katthe, A. Jahangiri, S. Ghanipoor Machiani, A. Ahmadi, & W. Musial. (2021). “Safety Impact Evaluation of Narrow AV-Exclusive Lanes on Existing Freeways.” The 100th Annual Meeting of the Transportation Research Board & Record, Washington, DC.
- **Symposium presentation:** Katthe, A., S. Ghanipoor Machiani, & A. Jahangiri. (2020, Feb 28). Safety Impact Evaluation an Automated Vehicle Exclusive Lane on I-15; Crash Data Analysis. Presented at *SDSU Student Research Symposium (SRS).*
    - Anagha Katthe won the Research Awards for Diversity, Inclusion and Social Justice at SRS.
- The project’s PI, Sahar Ghanipoor Machiani, won the 2020 San Diego County WTS Technology for Transportation Award for this project. This award recognizes projects that embrace new technological solutions shaping our transportation system and improving the quality of life for users and communities in San Diego County.
- The project won the 2020 ITE San Diego and the 2021 Western District ITE Transportation Achievement Award in Transportation Systems Management and Operations (TSMO).
- A brochure from the project’s recommendations was developed.

Data Products

This study has not generated any specific dataset. The data used in this study are publicly available at the NHTSA database and the Berkley Crash database.

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Appendices

Appendix A: I-15 Express Lanes Configuration

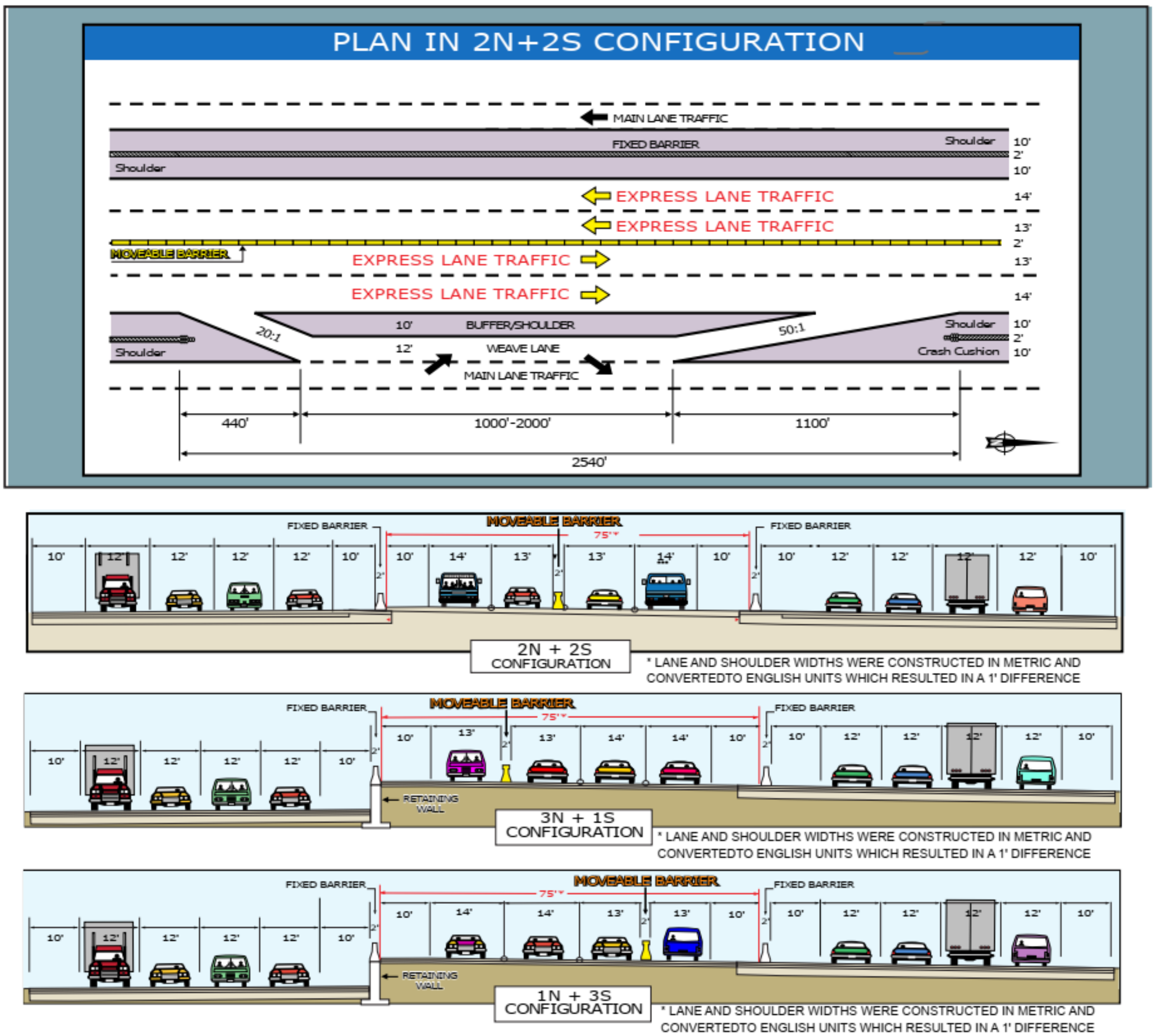


Figure 7. I-15 Express lanes existing 4-lane configurations [plans courtesy of Caltrans].

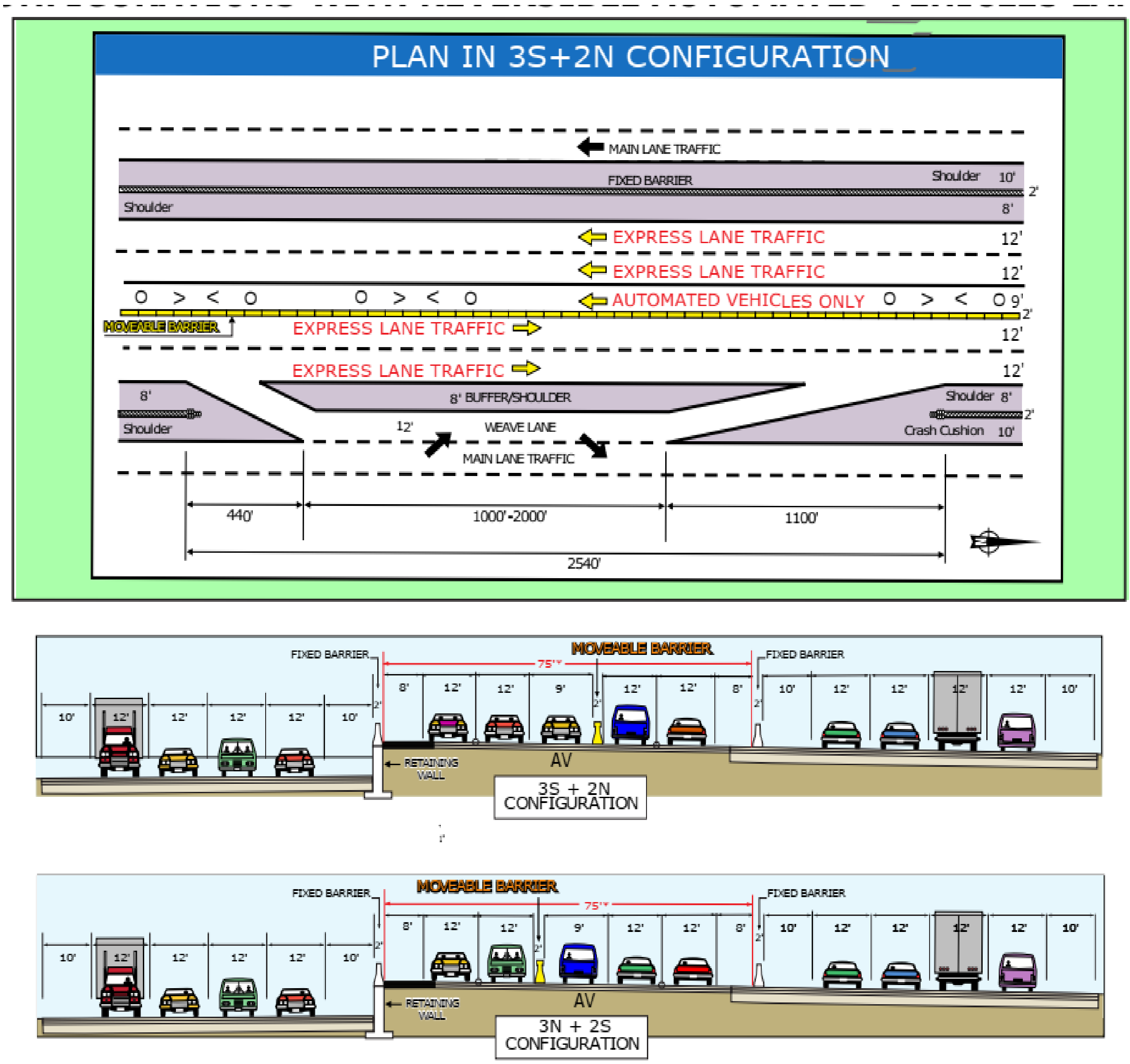


Figure 8. I-15 Express lanes configuration with reversible AV lane [plans courtesy of Caltrans].

Appendix B: Literature Review

For the safe and effective introduction of automated vehicles (AV) onto a dedicated narrow (9-foot) lane on the I-15, a thorough understanding of AV sensor technology capabilities, safety considerations of narrower lanes, and of existing AV-infrastructure interaction research must be obtained. This literature review will consider existing research in the development of AV environmental perception technologies as it relates to lateral control, and current literature examining recommendations of infrastructure improvements to support AVs.

One of the greatest challenges facing AVs was and continues to be in the navigation of a route and staying within a prescribed path or lane. The motion of an AV is comprised of lateral and longitudinal control. In conventional vehicles, the human driver directs these control tasks. In AVs they are governed by computers. Lateral control is the aspect of the motion of the vehicle that is key to staying in a lane. Lateral control technologies have developed iteratively, evolving from lane departure warning systems to lateral assist systems to lane centering systems.

Lane Departure Warning Systems

Lane Departure Warning (LDW) systems, one of the oldest and most developed autonomous vehicle attributes, only warns the driver that their vehicle is departing from the intended lane. LDW systems are dependent on the vehicles ability to perceive the environment around itself. Almost all LDW systems use some form of optical camera that focuses on lane markings. The differentiation of LDW systems is in environmental perception strategies, algorithms and supporting or reinforcing systems (i.e. coupling with GPS, etc.)

Amditis et al. (*17*) developed a lane departure avoidance system that is capable of handling varying traffic conditions. Through the use of environmental perception sensors such as cameras, radar, laser scanners and GPS, input data is collected and perceived, a decision is formulated, and action is taken by the vehicle controller. Cualain et al. (*18*) present a LDW system with an image processing method utilizing multiple optical cameras. The authors found the proposed system to be more robust than single cameras systems with higher detection rates. The proposed system used a lane segmentation strategy with a modified subtractive clustering algorithm. Zhang et al. (*19*) proposed an LDW system based on a camera supported analysis of grayscale distributions. An Advance Reduced Instruction Set Computing Machine (ARM) based platform was used to execute a lane departure risk evaluation model based on lasting time and frequency. Field tests yielded sufficient lane detection results.

Some research has been conducted to make LDW systems more accessible to a variety of consumers and vehicles. Pei-Yung Hsiao et al. (*20*) created a handheld LDW system that can be mounted on vehicle dashboards. The algorithm developed, uses a peak finding method with feature extraction that determines lane boundaries.

As LDW technology matured, research started to focus on the refinement of the systems as well as making them more robust by coupling with other technology. Clanton et al. (*21*) explored coupling LDW with GPS technologies for enhanced LDW system accuracy. The controller system measured GPS error utilizing the LDW, enabling it to develop correction measures. In the event that the LDW system failed, using the precalculated correction measures, the GPS would assist in LDW functions until the LDW reestablished function. Enache et al. (*22*) proposed an active steering assistance system that acts as both a lane departure avoidance and a lane keeping system. The authors' focus was on the lane keeping performance of the steering assistance system while under the driver's control of the vehicle. The advancement of the LDW technology paved the way for more complex systems necessary for AV lateral control.

Lane Keeping Assist

Lane Keeping Assist (LKA) was the next step in autonomous lateral control development. These systems both warn and then assist the driver to return to the center of the lane if drifting is detected. The research for LKA served as the basis for future lane centering technologies, where the vehicle is actively conducting lateral control. The challenges for LKA and lane centering systems are largely the same, that of perceiving the environment and processing the information fast enough to aide in controller decision making. Wang et al. (*23*) explored the challenge of time delay associated with cameras processing of imagery at different sampling rates impacting vehicle lateral control. The author presented a combined vision vehicle model to address the low sampling frequency and varying time delay of the geometrical-model based state calculation method. Field tests of the proposed methodology showed that the system updated lateral position faster than current on-board measurement systems.

Zhao et al. (*24*) proposed a two-level vehicle lateral control system, where the upper level develops a desired steering angle based on perception information from vehicle sensors. A multi-model fuzzy control algorithm was designed for lane tracking tasks in both the lane keeping and lane changing controllers. The lower level controller utilizes the calculated steering angle and generates the control signals for the steering actuators. As LKA system matured, more focus was directed to their performance in all conditions. Mustaki et al. (*25*) propose an optimized lane centering assist system (LCAS), (note as the author describes LCAS, it is functionally a LKA system), that utilizes a multi scenario approach to consider performance when the system is affected by environmental factors (wind, curves, etc.), which was then tested in simulation.

Lane Centering

As fully autonomous lateral control is the end state for AVs, most recent research on lateral control focuses on lane centering. Pendleton et al. (*26*) conducted an expansive literature review of current systems and algorithms pertaining to the operation of AVs. Of particular interest, the authors delved into detail the efficacy of various AV environmental perception systems such as LIDAR, cameras, INS/INU and GPS. The authors also explore the various vehicle control strategies, with emphasis on geometric controls and model-based methods. Vehicle localization and the lack of updated topographic maps was identified as the overarching challenge to the system; however the author notes advances in simultaneous localization and mapping (SLAM) that may address this.

Environmental perception is a key aspect of lane centering with ever increasing and more sophisticated research devoted to the topic. Ismail (*27*) discussed the design and implementation of the BlueBox computing system which enables the real-time perception capabilities of autonomous vehicles. Using various subsystems and sensors, the lane centering assist system provides lane detection and tracking, and is also capable of providing active steering to keep the vehicle automatically centered. The external environment is detected through forward facing cameras and then steers to keep on track through lane detection and tracking algorithms. Berriel et al. (*28*) proposed a vision based, real-time ego-lane analysis system that is capable of estimating ego-lane position, classifying lane marking types and road striping, performing lane departure warnings and detecting lane changing events. The proposed system combines a number of environmental detection systems (cameras) using a single algorithm. Working in a temporal sequence, lane striping features are extracted from the cameras and a final estimated lane is calculated into a spline.

Broggi et al. (*29*) sought to address the challenge of designing a general-purpose path planner and an associated low-level control for autonomous vehicles operating in unknown environments. The model developed considered obstacle detection, ditch localization, lane detection and global path planning. The vehicle environmental perception sensors helped generate a cost map which weighs obstacles and helps determine the traversable areas. To address the time delay associated with processing the perception data, way point coordinates were established for the drivetrain to follow, considering vehicle dynamics and path tracking information. The model exhibited a mean cross track error of 0.13m in autonomous tests and 0.17m in leader follower mode.

These lateral control systems are predominantly vision based, with capabilities beyond just lane detection, notably obstacle detection. The ability to detect obstacles is essential for AVs to avoid debris in the roadway as well as to aid in avoidance of side swiping collisions. To address the reality of dynamic driving conditions some researchers have sought to make controllers more responsive. Lee and Litkouhi (*30*) discussed an automated lane centering and changing control algorithm that focused on enhancing the control accuracy of the vehicle. The proposed algorithm is capable of providing smooth and aggressive lane centering/changing maneuvers according to current traffic conditions and driver preferences. The generated path could be recalculated for smoother or more aggressive lateral motion control.

Lateral control research has also considered the role of the vehicle's drivetrain and handling characteristics, particularly when it pertains to active steering to maintain the vehicle in the center of the lane. Most research previously simplified the vehicle model to act as a bicycle, meaning each axle was modeled as one wheel. Chebley et al. (*31*) presented a coupled control algorithm for longitudinal and lateral dynamics of an AV. Unlike most models which simplified vehicles to the bicycle model, their algorithm considered all parts of the vehicle and their interconnectedness. The algorithm used Lyapurov functions to ensure robust tracking of the reference trajectory/path in lane changing actions as well as obstacle avoidance and lane keeping. The objective of minimizing lateral displacement error whilst maintaining a desired longitudinal speed was achieved by generating a steering angle and a driving/braking torque that enable successful tracking of the reference trajectory. Attia et al. (*32*) posited an automated steering strategy based on nonlinear model predictive control. This strategy simultaneously considered the power train dynamics to manage the longitudinal speed tracking challenge in order to improve combined control. The prediction model calculates the future states of the dynamic system on a fixed finite time horizon. Tested in simulation against a predefined GIS trajectory, the lateral position error of the vehicle never exceeded 6 cm, whilst heading angles are admissible and longitudinal speed is correctly tracked.

Xu et al. (*33*) and Filho et al. (*34*) were concerned with maintaining fidelity of the desired track with the predicted track of the lane centering system. Xu et al. addressed lateral control by developing a sliding mode control to manage vehicle dynamics at high speeds. The drive control system used a parameterized cubic spline interpolation function to calculate a desired vehicle trajectory. In field tests, the system exhibited a max lateral position error of 0.5m, with most error below 0.2m when compared against a predetermined GPS trajectory. Filho et al. proposed a simplified control system for AVs that relied on a reduced number of parameters that could be set. To address lateral control, a cubic Bezier curve is utilized to correct the trajectory between the origin of the vehicle and the desired path. During field testing, approximately zero mean cross track error and an orientation error of -1.0397 degrees to 0.9225 degrees was observed.

AV Considerations and Initiatives

The rise of AVs has sparked considerable interest both in academic and government circles about their potential impact on the transportation system. Government agencies sought to frame the challenges of AV operations and their impacts on society. This also extends to currently deployed technologies as well. Brewer et al. (*35*) proposed a framework for the analysis of lane centering systems. This proposal was codified in the NHTS Functional Assessment of the automated lane centering (ALC), identifying five vehicle level safety goals, 47 functional safety requirements, and 26 additional safety requirements.

Focusing on safety, Giuffre et al. (*36*) consider the benefits and costs associated with AV technology in context of safety improvements on highways. The authors posit that autonomous vehicles have the potential to reduce time headway, thus enhancing traffic capacity and improve safety margins in car following. They also identified crash safety factors such as cyber-attacks, systems failures and database deficiency that must be considered. Finally, the authors conducted a microsimulation of mixed conventional and autonomous vehicles. New autonomous vehicle centric accident modification factors are recommended.

The FHWA (*37*) compiled a report with the purpose of assessing the needs of AVs on roadways. The report identified the need for standardization of signage, as well as lane marking. The report noted that the white lane markings surrounded by black paint has been effective in aiding AV lane navigation. The report also emphasized the importance of mapping roads, as effectively demonstrated by several carmakers. Additionally, in regards to rural areas, the report recommends the development of vehicle to infrastructure (V2I) improvements to transmit map and roadway conditions.

Recommendations for infrastructure improvements are not limited to government agencies or academic institutions. (*38*). Private industries in roadway materials suppliers and automotive makers are advocating for infrastructure improvements to support machine vision. These companies argue for increased cooperation and joint planning between vehicle manufacturers and infrastructure owners in infrastructure improvements. Special emphasis is placed on stripping, signage and V2I.

Finally, the functional impacts of AV deployment are also beginning to be considered. Hamilton et al. (*15*) focused on identifying and evaluating opportunities, constraints and guiding principles for implementing AV lanes. Utilizing a simulator-based model, the researchers identified parameters and variables that were sensitive to dedicating lanes to AV users and identified expected impacts under various conditions. Lanes were delineated based on AV market penetration rates by using "lane friction,"- speed differential between the dedicated lanes and adjacent general-purpose lanes- as a safety measure. The authors posit that AVs will benefit most from dedicated lanes (DL) when AV market penetration is low. Recommendations include: 1) shared DL with HOVs at lower market penetration rates, 2) exclusive DLs at medium market penetration (20-45%), and 3) no DLs for higher market penetration.

Using computer simulation, Ye et al. (*39*) examined traffic flow throughput on various dedicated AV lane configurations on a three-lane highway. The researchers found that it is most beneficial for traffic flow throughput with one CAV DL when CAV market penetration rate exceeds 40% and two CAV DLs when CAV market penetration exceeds 60%. It was also discovered that at lower market penetration rates, CAV DLs had a negative impact on the overall throughput, yet at very high CAV penetration rates, positive effects on flow and density also decrease.

The integration of AVs into transportation systems has garnered attention both in various departments of transportation within the United States and abroad. Many of the challenges and concerns with AVs operating on roads with regular vehicle traffic are identified and examined in similar fashion around the world.

The Victoria Transport Policy Institute (*40*) created a report that examined the major risks, benefits and planning consideration for autonomous vehicles as they deploy onto public rights of way. Potential risks identified include: hardware and software failures, malicious hacking, and platooning risks (i.e. increased crash severity due to higher vehicular densities and risks associated with human drivers entering platoons). The report cites/recommends that for platooning of AVs to be safe and effective, dedicated AV lanes may be required. The European Road Assessment Programme (*41*) developed a comparison between how AVs and human operated vehicles behave and react in various safety related scenarios. Various influencers in AV crash configuration/scenarios are considered as well as corresponding infrastructure attributes. The authors advocate the need for clear and consistent signage that is well maintained, as well as for clear and robust striping. Additionally, investments in connectivity of infrastructure are also stressed.

Some transportation agencies are taking concrete action in the integration of AVs on surface roads. Near Columbus Ohio, the Ohio Department of Transportation (*42*) (*43*) (*44*) is spearheading an AV infrastructure initiative that will build a 35-mile-long fiber optic cable with WIFI and Direct Short-Range Radio (DSRR) transmitters capable of communicating with CAVs. These transmitters will be spaced 600m apart and will assist in AV travel on this economically important transportation corridor. These infrastructure investments are not limited to the United States, with

China earmarking significant investments in AV infrastructure. A new highway connecting Beijing and the Xiongan New Area in Hebei province, China is being constructed that will have dedicated lanes for AVs. (*45*) The 100-kilometer (62 mile) eight lane freeway will support bi-directional traffic, with two lanes designed for AVs, operating at speeds between 62 to 74 mph. The highway will also incorporate intelligent road infrastructure and smart-toll facilities, which can collect vehicular and road information through WIFI technology, potentially improving the flow and safety of the system.

Appendix C: Review of AV Lateral Control Systems Using Manufacturers' Manuals and Websites

SAE Level 1-2

According to the SAE, level 1 Automation (Driver Assistance) is defined as "Vehicle is controlled by the driver, but some driving assist features may be included in the vehicle design." Level 2 (Partial Automation) is defined as "Vehicle has combined automated functions, like acceleration and steering, but the driver must remain engaged with the driver tasking and monitor the environment at all times"(*46*), (*47*). The majority of vehicles examined in this review fall into one of these two categories. For many vehicle manufacturers, automation levels are achieved gradually and sequentially. Cars with driver assistance features, such as lane departure warning systems or blind spot monitors, are deployed at level 1. Subaru, Mitsubishi and Kia currently fall into this category. All three currently have lane departure warning systems, which only alert the driver to drifting. These systems are typically dependent on optical cameras monitoring lane striping and only are effective at speeds above 45mph. The manufacturers do not specify how accurate their systems are in the performance of their duties.

Level 2 AVs are increasingly common. Most of the technology, such as lane centering and adaptive cruise control, are driver-assistance oriented and require the continued attention and situational awareness of the driver. Lane centering is an evolution of lane departure warning systems; in lane centering the vehicle applies a torque to the steering wheel when the vehicle senses that it is not in the center of the lane or is drifting. Most of the manufacturers have vehicles with mutually supporting environmental perception sensors. For example, Toyota's Safety Sense suite of technologies combines GPS, LiDAR, RADAR, and cameras for environmental perception and navigation (*48*). As the costs of developing AV technology are intensive, some companies share their technology amongst smaller firms. GM and Honda now share AV technology and research (*49*); Chrysler, Fiat and Jeep use the same Lane Sense suite of technologies (*50*), (*51*), (*52*). GM's SuperCruise, currently only deployed on Cadillac vehicles, is one of the most highly regarded systems, but its AV technologies, such as Lane Keep Assist (active automated steering to keep the vehicle centered in the lane), are limited to previously mapped roads (*53*), (*54*). GM is the only manufacturer at level 2 which provides measures of accuracy, claiming that its system can keep a vehicle within 5cm of the center of a lane. Toyota is developing a tiered system, dubbed the Guardian and Chauffer (*55*). The Guardian concept is at level 2, building on the previous Safety Sense technology, which incorporated a pre-collision system, Lane Departure Alert, Lane Tracing Assist, Dynamic Radar Cruise Control, and Sign Assist.

SAE Level 3

Some vehicle manufacturers are slowly progressing towards level 3 autonomy, most notably Tesla, Toyota, Uber, and Waymo. SAE defines level 3 (Conditional Automation) as "Driver is a necessity, but not required to monitor the environment. The driver must be ready to take control of the vehicle at all times with notice." AV technology at level 3 builds on the experiences from level 2 preceding it. Most of the manufacturers have vehicles with mutually supporting environmental perception sensors, combining GPS, LiDAR, RADAR, and cameras for perception and navigation tasks. These more advanced systems also employ complex AI software that predict the actions of the environmental actors in real-time to aid in navigation and in maneuvering to avoid threats. These AI systems are trained through machine learning. In WAYMO's case, test vehicles are driven throughout a designated test area and map and learn the surrounding environment (*56*). A safety driver is always available. Waymo claims an accuracy of 1 inch to their GPS tracks, and sensors can detect the surrounding environment up to 300 yds away.

At level 3, the philosophies of the manufacturers diverge significantly. Tesla gradually updates its vehicles, ever increasing its AV capabilities. Tesla's market penetration continues to expand, with an underlying philosophy that individuals will continue to own and operate private vehicles, a philosophy also shared by Toyota. WAYMO came to the conclusion after testing, that individuals would consistently fail to maintain the appropriate attention to the road, thus unable to safely take control of the vehicle in potentially dangerous circumstances (e.g., drifting). Consequently, it is WAYMO's goal to develop fully automated vehicles (level 4 and 5) prior to releasing them to the market. WAYMO (in partnership with Lyft) and Uber intend to use their AVs for ride hailing and delivery services (*57*), (*58*).

At level 3 and higher, safety issues due to AV technology become more apparent. Tesla has had at least 4 fatal accidents related to AV technologies and Uber has had 1 fatal accident. Preliminary investigations revealed that drivers failed to maintain sufficient environmental awareness and that the vehicles failed to distinguish unsafe environmental circumstances. In two of the Tesla incidents, the vehicles (and the driver) failed to recognize a semi-truck crossing a freeway. In another accident, the Tesla could not properly distinguish lane markings and slammed into a barrier (*59*), (*60*). In the Uber accident, the vehicle and the driver failed to recognize a pedestrian crossing the road at night (*61*). These incidents make clear that the technology is not foolproof and requires the complete attention of the driver at this time.

SAE Level 4/5

SAE defines level 4 automation (High Automation) as "The vehicle is capable of performing all driving functions under certain conditions. The driver may have the option of controlling the vehicle." Similar to level 3, few vehicle manufacturers have fully operational level 4/5 models, however, models are in development at Tesla, Toyota, Uber, WAYMO, and several smaller firms. WAYMO's capabilities and philosophy is detailed above. Toyota has had several research initiatives in AVs, most notably its Mobility/Highway Teammate and Platform 4.0 programs (*62*), (*63*), (*64*). These programs explored fully autonomous vehicles, culminating in its Chauffer program which operates at level 4/5 and will serve as a testbed for future research. Uber's technological capabilities are not described in detail, however it is known to use sensors, mapping and predictive motion planning (*65*). Limited real-world testing is conducted by Uber, WAYMO and Toyota, amongst others. level 4/5 vehicles are expected to take several more years of development prior to being widely deployed and commercially viable.

Summary Table of Reviewing AV Lateral Control Systems Using Manufacturers' Manuals and Websites

Vehicle Make	Model	Vehicle Type	Level of Automation	Year Range	Special Features/Tech	Level of Accuracy	Environmental Perception Sensors	Notes
Cadillac	CT6	SUV	Level 2	2018-present	SuperCruise- can only be engaged on pre-mapped highways. SuperCruise contains: Lane Keep Assist ("Blue Line"), Departure Warning, and Adaptive Cruise Control.	Claims 5cm scan accuracy	LiDAR map data is matched to cameras, GPS, RADAR	This system doesn't use LiDAR for environmental perception, but does utilize LiDAR derived maps. Maps are generated by GM, and updated by OnStar subscription. AV systems requires eyes on road (monitors eye movement) for hands free operation.
Tesla	S, X, Y, 3	Car, SUV	Level 2 -3	2014-present	Enhanced Autopilot- can be engaged anywhere, requires hands on wheel. Ability to conduct lane changes by engaging turn signal. Navigation functions collect data for mapping.	-	RADAR, Ultrasonic sensors, 8 external cameras	Allegedly in development for Level 5 automation.
Toyota	Corolla, RAV-4, Yaris,	Car	Level 2	2015-present,	Safety Sense incorporates pre-collision system,	-	Cameras, LiDAR, RADAR, GPS, Inertial Navigation	Corolla has lane keeping technology that is similar in concept to GM's

Vehicle Make	Model	Vehicle Type	Level of Automation	Year Range	Special Features/Tech	Level of Accuracy	Environmental Perception Sensors	Notes
	Camry, Prius, Avalon, Sienna				Lane Departure Alert, Lane Tracing Assist, Dynamic Radar Cruise Control, Sign Assist		Unit (INU). Attempts to predict the behavior of vehicles around the car.	SuperCruise. Note that Lane Tracing Assist and Road Sign Assist are entering the market for 2019.
Toyota	Prototype "Mobility Teamate" and “Highway Teamate”	Car, currently Lexus test vehicle	Level 2-3	2015-present		-	Cameras, LiDAR, RADAR, GPS, Inertial Navigation Unit (INU). Attempts to predict the behavior of vehicles around the car.	Mobility Teammate Concept: Toyota believes that interactions between drivers and cars should mirror those between close friends who share a common purpose, sometimes watching over each other and sometimes helping each other out. Toyota refers to this approach as the Mobility Teammate Concept. This approach acknowledges the utility of automated driving technologies while maintaining the fun experience of driving itself.
Toyota	Platform 4.0 or P4: modified Lexus LS 500h	Car	Level 2 and 5	2019	Guardian and Chauffer; Guardian is meant as Level 2, while Chauffer will be level 4-5.	-	2 side cameras to improve situational awareness on the sides, 2 imaging sensors – one facing forward and one pointed to the rear.	P4 is being used to test both the Guardian and the Chauffer systems. Guardian works with the driver as a teammate, still requiring driver interaction and intervening only in

Vehicle Make	Model	Vehicle Type	Level of Automation	Year Range	Special Features/Tech	Level of Accuracy	Environmental Perception Sensors	Notes
							The imaging sensors feature new chip technology with high dynamic range. Radar system, LiDAR sensing system with 8 scanning heads.	dangerous circumstances. Chauffer is meant to operate completely autonomously and will serve as a testbed for fully autonomous functions; evolution of Mobility Teammate Concept.
Toyota	e-Pallette	Car	Level 5	2018-present	Design for TNC and food deliver services	-	Cameras, LiDAR	
Nissan, Infiniti	Leaf, Rogue, QX50	Car, SUV	Level 2	2018-present	Design for TNC and food deliver services		Forward facing RADAR, cameras, sensors, steering assist	Propilot Assist: Stop-and-go adaptive cruise with lane-centering steering all the way to a stop, steering assist and Lane Departure Prevention technology.
WAYMO	Modified vehicles	Vans	Level 2 -3. Ride hailing focus on achieving Level 5	2009-present	Waymo system is largely focused on developing fully automated vehicles with no human interaction. Main concern was that people fail to pay attention. Drive, steer, and brake by wire. Predicts the behavior of	Claimes accuracy of 1 inch. Sensors can detect environment up to 300 yds away.	3 LiDAR systems, RADAR sensors, 8 cameras, use of predeveloped maps	Can only drive on pre-mapped courses. 3D Maps are generated by test vehicles. As of June 2019, Waymo agreed to build AVs for Nissan and Renault. Currently in partnership with Lyft in Phoenix, AZ.

Vehicle Make	Model	Vehicle Type	Level of Automation	Year Range	Special Features/Tech	Level of Accuracy	Environmental Perception Sensors	Notes
					vehicles, objects around the car.			
Uber	modified vehicles	Cars and Vans	Level 4-5				Utilizes mapping, prediction, and motion planning software.	Uber is focused on AVs for ridesharing purposes.
BMW	7- Series	Car	Level 2	2016-present	Lane guidance assist, and Lane Departure Warning.		5 radar sensors, 1 camera. Systems are only active if hands are on the wheel.	Lane guidance system steers independently; depending on speed, system orients itself according to lane markings and/or nearby vehicles. system vibrates the steering wheel when the vehicle unintentionally leaves its lane at speeds over 70 km/hr. 2 step approach, first haptic warning and brakes preconditioning, followed by automatic braking.
Hyundai	Genesis	Car	Level 2	2016-present	Lane Keep Assist System (LKAS)		Camera based LKAS	LKAS detects vehicle straying from lane. Visual (center console) and haptic steering wheel warning. LKAS only works if lane width is between 10' and 15'. Will not assist in sharp turns or in low visibility and foul weather conditions that may obscure view of lane markings. Applies torque to

Vehicle Make	Model	Vehicle Type	Level of Automation	Year Range	Special Features/Tech	Level of Accuracy	Environmental Perception Sensors	Notes
								steering wheel to keep vehicle in the lane. System shuts off below 40mph and above 110 mph. System only operates if two lane markings are detected. LKAS only starts to control wheel when near edge of lane marking.
Fiat	500x	Car	Level 2	2014-present	Lane Sense- an LKAS/LDWS system that is shared amongst Chrysler/Dodge vehicles.		Camera based LKAS	Applies torque to steering wheel. Intensity of assistance (i.e. jerk) can be adjusted to driver preference. Haptic (steering wheel) and visual warnings (center console). Operational above 37MPH and below 112MPH. Requires hands on the wheel.
Jeep	Cherokee	SUV	Level 2	2014-present	Lane Sense- an LKAS/LDWS system that is shared amongst Chrysler/Dodge vehicles.		Camera based LKAS	Applies torque to steering wheel. Intensity of assistance (i.e. jerk) can be adjusted to driver preference. Haptic (steering wheel) and visual warnings (center console). Operational above 37MPH and below 112MPH. Requires hands on the wheel.
Kia	Sedona	Vans	Level 1	2017-present	LDWS. Detection of lane markings above 44MPH.		Dashboard mounted camera	

Vehicle Make	Model	Vehicle Type	Level of Automation	Year Range	Special Features/Tech	Level of Accuracy	Environmental Perception Sensors	Notes
					Only serves as a warning system.			
Mitsubishi	Outlander	SUV	Level 1	2017-present	LDWS.		Dashboard mounted camera	Detection of lane markings above 38MPH. Only serves as a warning system. Audible warning upon departure.
Chrysler	Pacifica	Vans	Level 2	2014-present	Lane Sense- an LKAS/LDWS system that is shared amongst Chrysler/Dodge vehicles.		Camera based LKAS	Applies torque to steering wheel. Intensity of assistance (i.e. jerk) can be adjusted to driver preference. Haptic (steering wheel) and visual warnings (center console). Operational above 37MPH and below 112MPH. Requires hands on the wheel.
Subaru	Legacy Outback	SUV	Level 1	2017-present	LDWS and Lane Sway Warning		Camera based	LDWS- warns driver with 6 beeps and with visual warning. Operates above 30 MPH. Lane Sway Warning- detects excessive swaying above 38 MPH
Honda	Civic, Accord, CR-V (first one), Insight, Pilot, Fit,	SUV and cars	Level 2	2015-Present	Honda Sensing. Includes: Collision Mitigation Braking System, Lane Keeping Assist System, LaneWatch Blind		Camera and RADAR based	Invested into GM's Cruise program

Vehicle Make	Model	Vehicle Type	Level of Automation	Year Range	Special Features/Tech	Level of Accuracy	Environmental Perception Sensors	Notes
	Odyssey, Ridgeline				Spot Display, Adaptive Cruise Control, Lane Departure Warning. Select 2018 onward will have also Honda LaneWatch, Blind Spot Information System, Cross Traffic Monitor, Auto High-Beam Headlights			
Dodge	Durango, Charger, Journey	Van, Car, SUV	Level 2	2014-present	Lane Sense- an LKAS/LDWS system that is shared amongst Dodge vehicles.		Camera based LKAS	Applies torque to steering wheel. Intensity of assistance (i.e. jerk) can be adjusted to driver preference. Haptic (steering wheel) and visual warnings (center console). Operational above 37MPH and below 112MPH. Requires hands on the wheel.

Appendix D: Expert Questionnaire

Based on your professional affiliation, please provide your answers to questions under the category of (1) academia and transportation officials or (2) manufacturers/technologists. If you have no input for any question, please enter "NA".

(1) Academia and Transportation Officials

1. What benefits and disadvantages do you foresee with dedicated AV lanes in general and with regards to the plan depicted above?
2. What are the uncertainties and or limitations associated with AV environmental sensor technology, and how would these limitations/concerns affect safe AV operation in a narrow (9-ft) lane?
3. Are you aware of any study results that compares lateral control performance of human-driven vs AVs?
4. Will adverse weather conditions significantly degrade AV's ability to perform lateral control functions in narrow lanes? If so, what are some recommended restrictions or guidelines in the event of adverse weather conditions? What redundant sensor/navigation systems are in place to address lateral control function in adverse weather conditions? How similar or different it is during snow/fog/ wet pavement conditions?
5. Are there any limitations associated with roadway geometry, narrow lanes and speed considerations for automated vehicles? (e.g., is there a limit to the radius/angle of a turn to avoid an automated vehicle from drifting out of its lane?)
6. Are there any restrictions/guidelines regarding lane width considerations for safe travel of automated heavy-duty vehicles (e.g. buses and trucks)?
7. What supporting infrastructure (markings, signage, roadside data transmission unit, etc.) will assist or enable an AV to operate in a narrow lane, especially adjacent to regular traffic lanes? Are these required for all levels of automation or only specific levels?
8. How robust are AV systems which include infrastructure non-idealities (e.g.: potholes, non-uniform lane markings or missing signages)?
9. What levels of autonomy should be allowed on the AV- exclusive lane?
10. What additions or revisions need to be made to existing vehicle standards and transportation design manuals regarding AV exclusive lanes? Are there any ongoing regulatory efforts that you are aware of?

11. At what point in market share penetration should AV exclusive lanes be considered? At what point should AV lanes be decommissioned?
12. How will the construction of a narrow (9-ft) lane affect the efficiency of traffic flow characteristics?
13. What is the foreseeable impact on the capacity of existing (normal) lanes as a result of AV lane implementation?
14. What are some safety concerns associated with implementing a narrow (9-ft) lane given the plan depicted above?
15. What education or training if any, should be implemented for AV exclusive lanes operation?

(2) Manufacturers/Technologists

1. What benefits and disadvantages do you foresee with dedicated AV lanes in general and with regards to the plan depicted above?
2. What are the uncertainties and or limitations associated with AV environmental sensor technology, and how would these limitations/concerns affect safe AV operation in a narrow (9-ft) lane?
3. Are you aware of any study results that compares lateral control performance of human-driven vs AVs?
4. Will adverse weather conditions significantly degrade AV's ability to perform lateral control functions in narrow lanes? If so, what are some recommended restrictions or guidelines in the event of adverse weather conditions? What redundant sensor/navigation systems are in place to address lateral control function in adverse weather conditions? How similar or different it is during snow/fog/ wet pavement conditions?
5. Are there any limitations associated with roadway geometry, narrow lanes and speed considerations for automated vehicles? (e.g., is there a limit to the radius/angle of a turn to avoid an automated vehicle from drifting out of its lane?)
6. Are there any restrictions/guidelines regarding lane width considerations for safe travel of automated heavy-duty vehicles (e.g. buses and trucks)?
7. What supporting infrastructure (markings, signage, roadside data transmission unit, etc.) will assist or enable an AV to operate in a narrow lane, especially adjacent to regular traffic lanes? Are these required for all levels of automation or only specific levels?

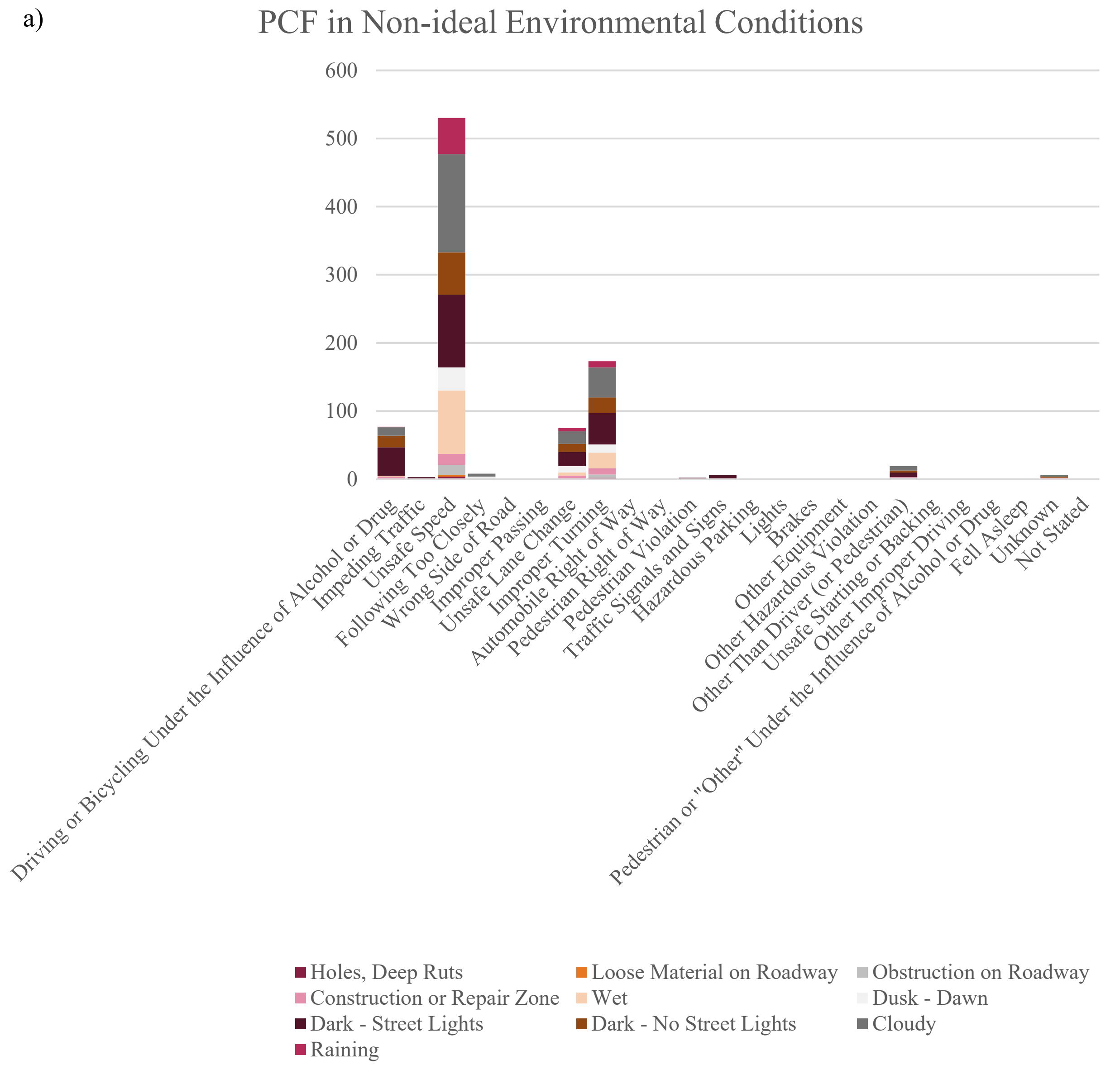
8. How robust are AV systems which include infrastructure non-idealities (e.g.: potholes, non-uniform lane markings or missing signages)?
9. What levels of autonomy should be allowed on the AV- exclusive lane?
10. What additions or revisions need to be included to existing vehicle standards regarding lateral control? Are there any ongoing related regulatory efforts that you are aware of?
11. At what point in AV market share penetration should AV exclusive lanes be considered? At what point should AV lanes be decommissioned?
12. What are the sensor thresholds for safe AV operation in narrow lanes? Specifically, what minimum lane width will cameras or other lane marking detection sensors be effective at?
13. Are there any specific requirements for efficient and effective working of AVs during night driving in relation to lateral control?
14. What are the remedial component redundancies available in AV to prevent catastrophic failure if some part of AV system, related to lateral control, fails (e.g.: multicore independent processor for self-driving computer)?
15. How is your lane keeping system level of accuracy codified and measured? What accuracy standards have been established for lateral control (even if internal to the company)? What internal standards are used to measure the accuracy of lane keeping systems? How is this tested?
16. Some agencies and municipalities use modified white lane markings enhanced with black stipes on the sides of solid or dashed white lines or preceding white dashed lines. Will such measures aid your AV in lateral control functions?
17. If GPS were to fail, would your AV still be able to safely operate on a narrow lane? How would it react?
18. What speed is optimal for safe operations of AVs in narrow lanes?
19. Given a scenario were an AV is operating in a narrow (9-ft) lane, could an AV safely respond to dangerous environmental stressors such as a lane splitting motorcycle or aggressive human drivers? How would it react?
20. If you think AV could not safely operate in a narrow (9-ft) lane, what minimum lane width is needed?

Appendix E: Crash Analysis Under Non-ideal Environmental Conditions

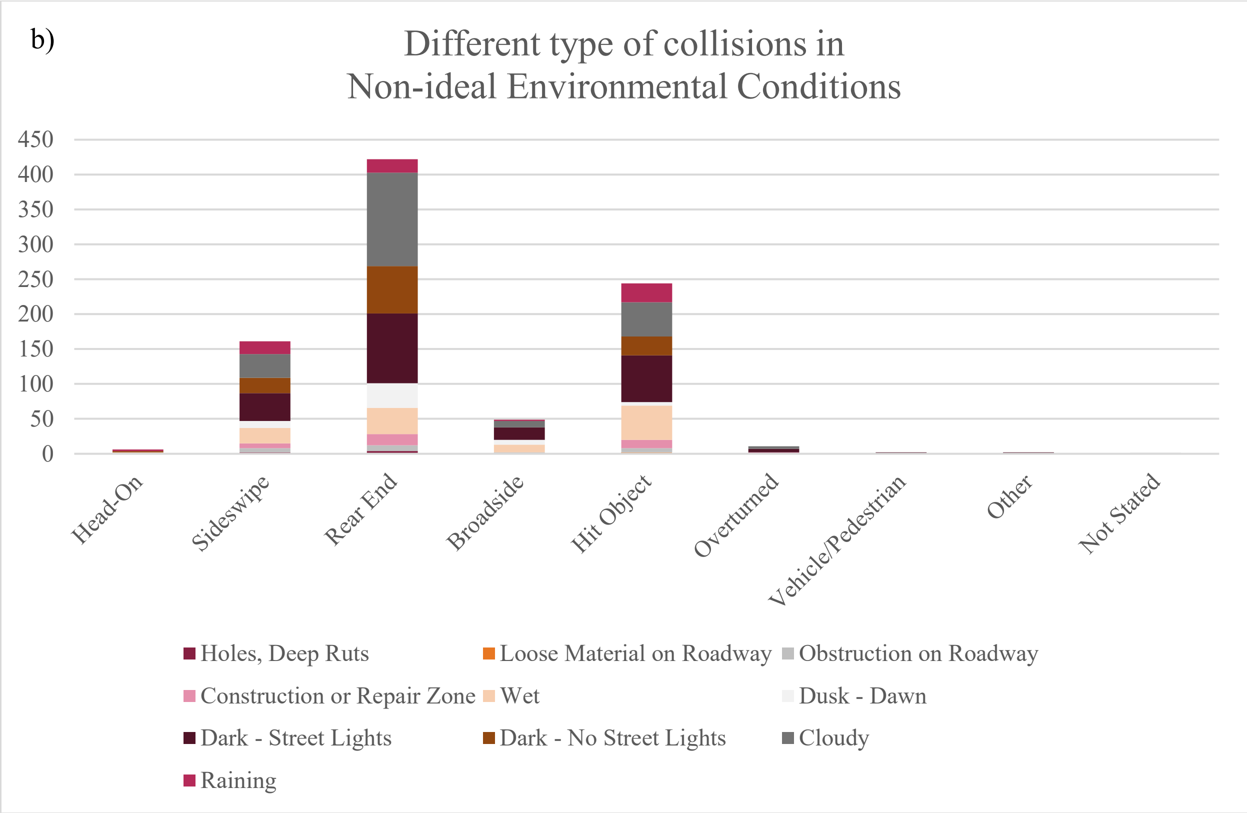
Environmental conditions play an important role in road safety. Non-ideal environmental conditions can directly or indirectly cause crashes, and this holds true for AVs as well. Non-ideal conditions such as wet surface conditions, dusk-dawn conditions and adverse weather conditions that includes cloudy, rainy, and dark (no/limited streetlight conditions) can severely limit the functionality of cameras and sensors in AVs on DL. Although AVs address many situations that human sometimes cannot perceive, it is still a challenge for AVs to perform efficiently and effectively under adverse weather conditions. Non-ideal weather and road surface conditions can cause detection errors, reduced sensor detection range, etc. AV automated systems, environmental sensors, and infrastructures need to be improved for more safety benefits in both fair and adverse weather conditions. However, in extreme weather and road conditions, AV-exclusive lane could be temporarily converted to GPL.

Comparing crashes under non-ideal environmental conditions (Figure 9) with all crashes (Figure 3), under non-ideal environmental conditions the same set of PCFs and collision severities are dominant in causing majority of the crashes as seen in Figure 9a and Figure 9c. However, hit object collisions were more than side swipe collisions as seen in Figure 9b. Therefore, the design methodology for AV-exclusive lane could be similar in varied weather conditions.

a)



PCF in Non-ideal Environmental Conditions
600
500
400
300
200
100
0
Driving or Bicycling Under the Influence of Alcohol or Drug
Impeding Traffic
Unsafe Speed
Following Too Closely
Wrong Side of Road
Improper Passing
Unsafe Lane Change
Improper Turning
Automobile Right of Way
Pedestrian Right of Way
Pedestrian Violation
Traffic Signals and Signs
Hazardous Parking
Lights
Brakes
Other Equipment
Other Hazardous Violation
Other Than Driver (or Pedestrian)
Unsafe Starting or Backing
Other Improper Driving
Pedestrian or "Other" Under the Influence of Alcohol or Drug
Fell Asleep
Unknown
Not Stated
Holes, Deep Ruts
Loose Material on Roadway
Obstruction on Roadway
Construction or Repair Zone
Wet
Dusk - Dawn
Dark - Street Lights
Dark - No Street Lights
Cloudy
Raining



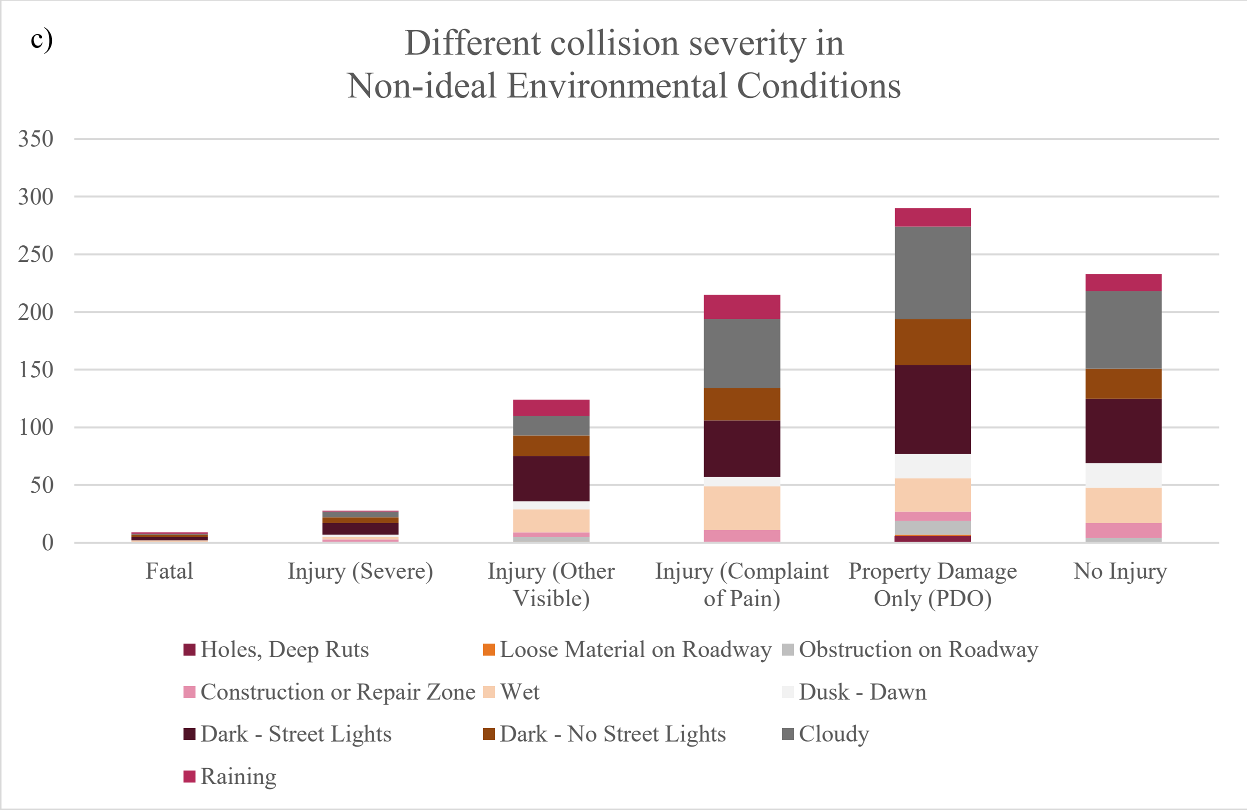
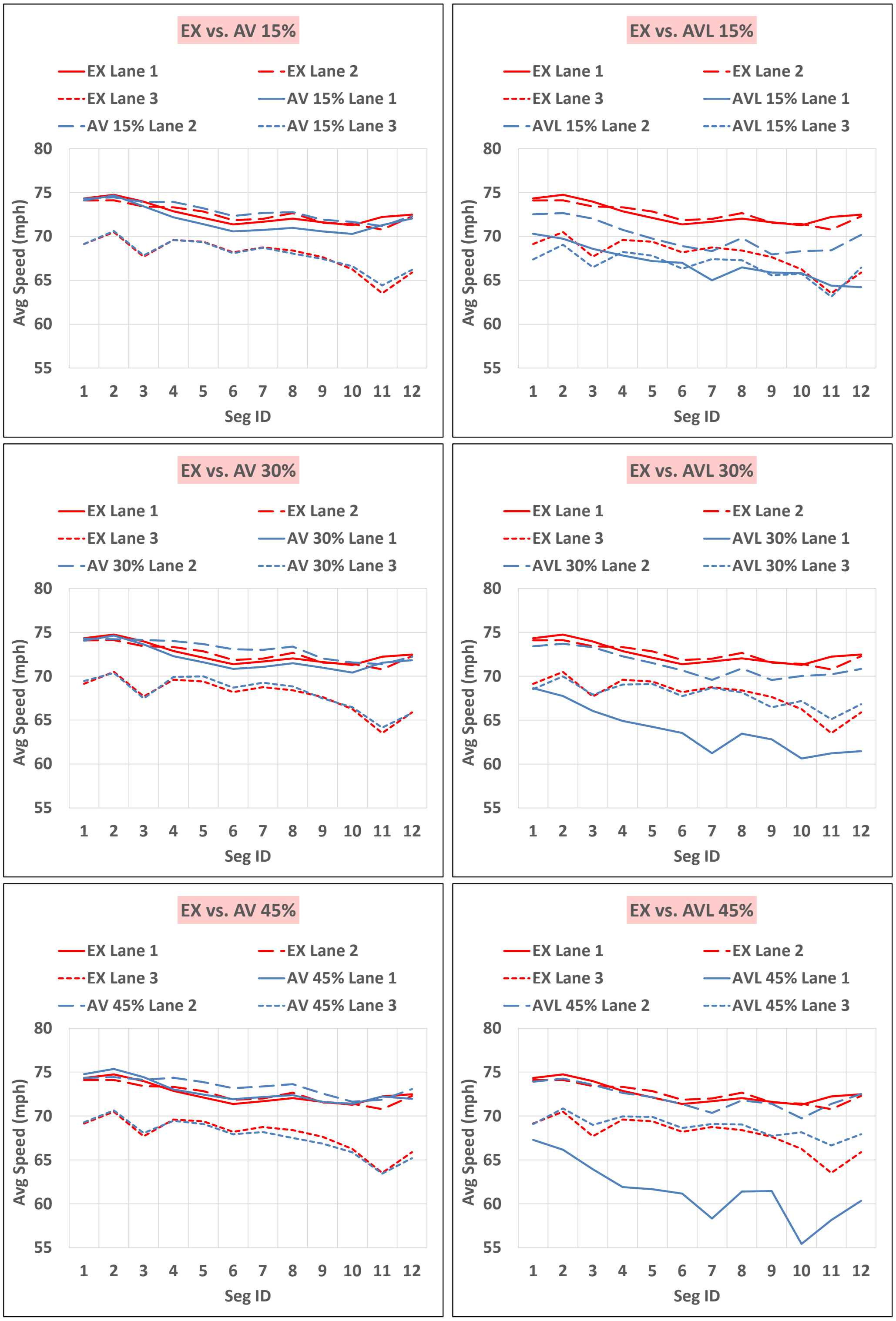


Figure 9. Non-ideal environmental conditions for AV a) PCFs b) Type of collision c) Collision severity

Appendix F. Speed Differential Graphs

Table 3. Traffic Flow Change from EX

Segment ID	Scenario 2			Scenario 3		
	AV 15%	AV 30%	AV 45%	AVL 15%	AVL 30%	AVL 45%
1	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
2	0.1%	0.1%	0.1%	0.0%	0.0%	-0.1%
3	0.0%	0.1%	0.1%	0.0%	-0.1%	-0.2%
4	-0.3%	0.1%	0.0%	3.0%	7.2%	10.7%
5	-0.1%	0.0%	0.0%	2.7%	6.9%	10.2%
6	-0.2%	-0.4%	-0.2%	2.8%	6.6%	10.0%
7	0.0%	-0.1%	0.2%	2.7%	5.9%	9.1%
8	-0.2%	0.2%	0.0%	3.0%	6.3%	9.9%
9	0.0%	0.4%	0.2%	2.8%	5.4%	8.4%
10	-0.4%	0.3%	-0.2%	2.1%	5.1%	8.3%
11	-0.3%	0.0%	0.2%	2.2%	5.1%	7.7%
12	0.0%	0.1%	-0.2%	4.4%	8.7%	13.6%


EX vs. AV 15%
EX Lane 1
EX Lane 2
EX Lane 3
AV 15% Lane 1
AV 15% Lane 2
AV 15% Lane 3
Avg Speed (mph)
Seg ID
EX vs. AVL 15%
EX Lane 1
EX Lane 2
EX Lane 3
AVL 15% Lane 1
AVL 15% Lane 2
AVL 15% Lane 3
Avg Speed (mph)
Seg ID
EX vs. AV 30%
EX Lane 1
EX Lane 2
EX Lane 3
AV 30% Lane 1
AV 30% Lane 2
AV 30% Lane 3
Avg Speed (mph)
Seg ID
EX vs. AVL 30%
EX Lane 1
EX Lane 2
EX Lane 3
AVL 30% Lane 1
AVL 30% Lane 2
AVL 30% Lane 3
Avg Speed (mph)
Seg ID
EX vs. AV 45%
EX Lane 1
EX Lane 2
EX Lane 3
AV 45% Lane 1
AV 45% Lane 2
AV 45% Lane 3
Avg Speed (mph)
Seg ID
EX vs. AVL 45%
EX Lane 1
EX Lane 2
EX Lane 3
AVL 45% Lane 1
AVL 45% Lane 2
AVL 45% Lane 3
Avg Speed (mph)
Seg ID