Advanced Driver Assistance Systems in Law Enforcement Vehicles

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

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14. ABSTRACT
Motor vehicle crashes are one of the leading causes of on-duty death for law enforcement (LE) officers, firefighters, and emergency medical service (EMS) personnel. This manuscript examines the potential benefits, limitations, and human factors considerations when implementing advanced driver assistance systems (ADAS) in LE fleets, with additional considerations when incorporating ADAS features in ambulances and fire trucks. We found that ADAS, specifically collision avoidance systems focused on longitudinal control and lateral control, are likely to significantly reduce crash risk in LE vehicles during normal driving scenarios. Conversely, collision avoidance systems may interfere with emergency driving and tactical driving maneuvers when active. Driver-vehicle interfaces for ADAS-equipped emergency vehicles should ideally have adaptive and flexible ADAS features that allow for their selective activation and deactivation based on situational needs. ADAS training for first responders should be multifaceted, including both general and specialized components to encourage accurate mental models.

15. SUBJECT TERMS
advanced driver assistance systems (ADAS), human factors, training, law enforcement, fire fighters, emergency medical personnel

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Abstract

Motor vehicle crashes are one of the leading causes of on-duty death for first responders such as law enforcement (LE) officers, firefighters, and emergency medical service (EMS) personnel. Emerging evidence suggests that vehicles equipped with advanced driver assistance systems (ADAS), specifically collision avoidance systems, exhibit a significantly lower crash risk relative to vehicles without those systems in the general population. Collision avoidance systems may offer similar potential to reduce crashes and save lives among first responders, but concerns remain that these systems may interfere with emergency driving and tactical maneuvers among law enforcement officers. This report examines the potential benefits, limitations, and human factors considerations of incorporating ADAS within LE fleets, with additional considerations given to ambulances and fire trucks. We found that collision avoidance systems focused on longitudinal control (forward collision warning and automatic emergency braking) and lateral control (blind spot monitoring, lane departure warning, and lane keeping assist) are likely to significantly reduce crash risk in LE vehicles during normal driving scenarios.

Conversely, collision avoidance systems may interfere with emergency driving and tactical driving maneuvers when active. Driver-vehicle interfaces for ADAS-equipped first responder vehicles should ideally incorporate adaptive and flexible ADAS features that allow for selective activation and deactivation based on situational needs. ADAS training for first responders should be multifaceted, including a general component which teaches fundamental information on ADAS technology relevant to crash investigations, as well as a specialized component specific to training first responders on the abilities and limitations of their particular vehicle and driving scenarios. ADAS training should consist of both an in-person classroom-based component in order to establish accurate mental models, and a practical in-the-field or simulator-based component to teach first responders how to use the human-machine interface to perform specific tasks with the ADAS as they operate the vehicle. Agentic AI applications may be particularly suited to enabling personalized ADAS training. Further research is necessary to understand the potential benefits and limitations of ADAS for LE and other first responders.

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Acronyms and Terms

Table 1. Acronym Definitions

Acronym	Definition
ABS	Anti-lock Braking System
ACC	Adaptive Cruise Control
ACSWS	Advance Curve Speed Warning Systems
ADAS	Advanced Driver Assistance Systems
ADS	Automated Driving System
AEB	Automatic Emergency Braking
BSM	Blind Spot Monitoring
CAD	Conditionally Automated Driving
DMS	Driver Monitoring Systems
DVI	Driver-Vehicle Interface
EMS	Emergency Medical Service
ESC	Electronic Stability Control
FCW	Forward Collison Warning
FLETC	Federal Law Enforcement Training Centers
HASS COE	Highly Automated Systems Safety Center of Excellence
HMI	Human-Machine Interface
LCA	Lane Centering Assist
LDW	Lane Departure Warning
LE	Law Enforcement
LKA	Lane Keeping Assist
MCT	Mobile Computer Terminal
NHTSA	National Highway Traffic Safety Administration
ODD	Operation Design Domain
PIT	Precision Immobilization Technique
RAB	Rear Automatic Braking
RCTB	Rear Cross-Traffic Braking
RCTA	Rear Cross-Traffic Alert
SAE	Society of Automotive Engineers
TRB	Transportation Research Board
TRID	Transport Research International Documentation

1 Introduction

Advanced driver assistance systems (ADAS) are a group of vehicle control technologies that aim to enhance driver experience and safety [1]. ADAS features include driver support features and active safety systems, as defined by SAE International in Levels 0, 1, and 2 of their taxonomy of vehicle automation [2]. This includes active ADAS that can automatically take control of certain vehicle functions, including longitudinal control of acceleration and braking (adaptive cruise control [ACC] and automatic emergency braking [AEB]), lateral control of steering (lane centering assist [LCA] and lane keeping assist [LKA]), or a combination of both. ADAS also includes passive systems that provide alerts to drivers without intervening with driver operations, such as lane departure warning (LDW) and forward collision warning (FCW). When a driver has either Level 1 or Level 2 ADAS features engaged, the driver must constantly supervise the automation and must always be ready for manual control. The National Highway Traffic Safety Administration (NHTSA) has mandated several ADAS features in all new vehicles, including electronic stability control (ESC) in 2012 [3], anti-lock braking systems (ABS) in 2013 [4], and backup cameras in 2018 [5]. NHTSA has additionally finalized a new rule mandating AEB on all passenger vehicles and light trucks starting in 2029 [6].

Research suggests that several ADAS features are effective in reducing crashes, fatalities, and injuries on roadways [7]. For example, the AAA Foundation for Traffic Safety and the University of North Carolina Highway Research Center estimate that existing ADAS technologies available to U.S. consumers could prevent around 37 million crashes, 14 million injuries, and 249,000 fatalities from 2021 to 2050 [8]. While the large-scale adoption of ADAS technologies exhibits immense potential for improvements in roadway safety, the effects of ADAS technologies on other aspects of public safety remain unclear.

On-the-job fatalities of law enforcement (LE) officers as a result of motor vehicle crashes increased by over 80% from 1980 to 2008, while LE officer deaths resulting from other causes decreased by about 50% over that time period [9]. LE officers face a traffic-related fatality rate that is three times greater than the national average [10]. Of note, the great majority of these crashes involving LE officers, between 60 to 81 percent, occurred during routine driving [11], [12].

Fire and emergency service vehicles, as well as specialized tactical vehicles used by LE in some scenarios, face distinct crash risks relative to most consumer and LE vehicles due to their weight. Ambulances weigh between 9,200 to over 14,000 pounds, with several types of ambulances meet the NHTSA standard as a heavy vehicle (greater than 10,000 pounds) [13]. Fire vehicles are even heavier, ranging from around 30,000 to 50,000 pounds for fire engines, with fire tankers exceeding over 60,000 pounds based on water capacity [14]. The weight of these heavy emergency vehicles makes acceleration and deceleration difficult, introducing risks at traffic intersections [15]. Specifically, heavy emergency vehicles experience a “Dilemma Zone” at intersections in which yellow light durations are often too short for heavy emergency vehicles to safely stop, increasing angular crash risk [15]. Heavy emergency vehicles also carry a higher risk of roll-over crashes due to their high center of gravity [15]. These factors contribute to firefighters and emergency medical service workers facing a much higher traffic-related fatality rate than the general population [10]. Specifically the traffic-related fatality rate relative to the national average is roughly three times higher in firefighters, and 4.8 times higher in emergency medical service personnel [10]. Further, approximately 25% of all fire service fatalities are comprised of vehicle-related deaths [16].

Based on this, ADAS technologies present an opportunity to save lives through prevention of collisions involving first responders[1] [17], [18]. However, emerging ADAS technologies may present novel and unexpected hazards to first responders while performing non-routine duties, such as emergency responses or pursuits by LE officers [17]. In such situations, ADAS technologies may interfere with and respond unsafely to drivers during instances of speeding, close proximity to other vehicles, and unexpected lateral maneuvers. For example, previous work has demonstrated that the incorporation of electronic stability control (ESC) in LE vehicles changed underlying vehicle dynamics during precision immobilization techniques (PITs), a technique used by LE officers in certain pursuit situations to immobilize a fleeing vehicle [19], [20]. This change in vehicle dynamics led to a high-risk maneuver becoming less predictable, increasing risk to LE officers, the driver of the fleeing vehicle, and surrounding pedestrians [19], [20].

The U.S. Department of Transportation’s Highly Automated Systems Safety Center of Excellence (HASS COE) and the Federal Law Enforcement Training Centers (FLETC) have entered into a memorandum of agreement to help FLETC prepare to effectively and safely engage with new transportation technologies while ensuring public safety. One area of interest identified in the memorandum is understanding ADAS in law enforcement operations, their applications, and limitations. With that in mind, the scope of this report includes background information on ADAS technologies available in police vehicles (Section 2), an examination of existing evidence on the effects and potential effects of ADAS on LE officers performing their duties, including daily operations, pursuits, traffic stops, emergency responses, and protective details (Section 3), the human factors considerations that arise when LE officers are operating vehicles equipped with ADAS technologies (Section 4), the implications of the above for training (Section 5), and emerging solutions and research gaps (Section 6). Because many of the above issues are

[1] First responders here and elsewhere unless otherwise specified is used to refer to law enforcement (LE) officers, firefighters, and emergency medical service (EMS) personnel.

general ones, applicable to the wide range of first responders, not only to LE officers, it is only when a topic is specific to a group of first responders that we will refer specifically to that group.

2 Background

The search strategy for background articles is described first (Section 2.1). Next, in order, we provide: an overview of ADAS features (Section 2.2), a review of ADAS feature availability in three common LE vehicle platforms (Section 2.3), a review of LE officers' perceptions of ADAS features (Section 2.4), and a description of driving challenges facing first responders (Section 2.5). Where relevant in these sections, information is given specifically to firefighters and emergency medical personnel.

2.1 Search Strategy and Scope

To address the potential benefits and tactical limitations of ADAS adoption and training among LE officers (and first responders in general), we conducted a narrative literature review. This search focused primarily on: 1) identifying any literature exploring ADAS perceptions and utility among first responders, 2) identifying and explaining the safety benefits of specific ADAS features demonstrated in the general population that may translate well to first responders, 3) explaining the human factors principles and associated driver-vehicle interface guidelines crucial to successful ADAS implementation in first responders, and 4) identify recommendations for ADAS-specific training in first responders. The literature review was focused on SAE levels 0 - 2 of vehicle automation [2]. Automated driving systems (ADS) that comprise SAE levels 3 – 5 were out of the scope of this review.

The initial Transport Research International Documentation (TRID) search used the following Boolean query:

- (("advanced driver assistance system" OR ADAS) AND ("law enforcement" OR "police " OR "first responder" OR "emergency response" OR "crash scene" OR "incident management" OR "firefighter" OR "Emergency Medical Services" OR "Emergency Medical Technician")) AND (vehicle OR automobile OR transportation)

This search resulted in 49 results from 2002 to 2025, 17 of which we deemed relevant to the literature review. Manufacturer website, guides, and owner's manuals for the 2025 Ford Police Interceptor [21], 2025 Chevrolet Tahoe Police Pursuit Vehicle (PPV) [22], and 2025 Dodge Durango Pursuit [23] were reviewed for feature functionality. Government reports, reports from private industry groups, and additional research articles were found using a snowball search strategy. Specifically, we used Google Search, Google Scholar and Google Scholar Labs to identify articles in specific areas of research mentioned above.

2.1.1 AI Assistance Disclosure

The authors utilized Google's NotebookLM to assist with the preparation of this manuscript. NotebookLM was used to aid in brainstorming manuscript organizational structure, organizing research notes, comparing ADAS features across different make and models of LE vehicles, and proofreading text for grammar, accuracy, and consistency. This tool was strictly used in an assistive capacity and was not used to draw independent conclusions. The authors thoroughly reviewed and validated AI-assisted content against source material. No passages in the manuscript were extracted from NotebookLM, as all text was generated by human researchers with the exception noted in Section 5.2 for responses generated from NotebookLM for the development of an agentic AI ADAS training program. The authors take full responsibility for the contents and accuracy of this manuscript.

2.2 Overview of ADAS and Relationship with Vehicle Automation

The industry-accepted taxonomy for vehicle automation categorizes vehicle automation across six levels ranging from level 0 (no automation) to level 5 (complete automation) [2]. Advanced driver assistance systems (ADAS) can fall within levels 0-2 (described in Table 2 below). At higher levels (3-5), called automated driving systems (ADS), the system is primarily responsible for the dynamic driving task (DDT) within its operational design domain (ODD), rather than the human [2]. For each level in Table 2, an explanation of the function of the ADAS feature is given along with examples.

Table 2. ADAS across SAE J3016 Taxonomy of Driving Automation Systems

SAE Level	Function	Examples
Level 0 – No driving automation	System provides warnings to and interventions for driver, but ***no sustained*** automation is provided for dynamic driving task	Forward Collision Warning (FCW), Automated Emergency Braking (AEB), Electronic Stability Control (ESC), Lane Departure Warning (LDW), Blind Spot Monitoring (BSM), Rear-View Camera, Rear Cross-Traffic Alert (RCTA), Rear-View Camera, Traffic Sign Recognition, Driver Drowsiness Detection, UI/infotainment (Bluetooth), Reverse Brake Assist (RBA), Rear Cross-Traffic Braking (RCTB)
Level 1 – Driver Assistance	System provides ***sustained*** lateral or longitudinal control (but not both) under driver supervision while driver performs all remaining tasks	Adaptive Cruise Control (ACC), Lane Keeping Assist (LKA), Lane Centering Assist (LCA)
Level 2 – Partial driver automation	System provides both sustained lateral and longitudinal control without driver input, but under driver supervision, while driver performs all other driving tasks	Adaptive Cruise Control with Lane Centering (ACC+LCA), Traffic-Jam Assist (stop-and-go ACC + lane centering), Automated parking (park assist with steering + throttle/brake)

While the SAE taxonomy on vehicle automation groups Level 0, 1 and 2 systems by what automation provides to the driver, researchers have proposed that a potentially more useful taxonomy would be grouping ADAS across functions that the driver needs to perform [24]. Researchers propose that ADAS can be classified based on dimensions of urgency and control [24]. Specifically researchers propose three general functions and several subcategories within those functions: control (longitudinal, lateral), monitoring (surroundings, occupants, vehicle), and information systems [24]. We separate these general functions and subcategories into four sections: longitudinal control, lateral control, monitoring, and additional automated systems unique to law enforcement. The categorization is not exhaustive and is focused on capabilities related to first responders. A more thorough list of ADAS can be found elsewhere [24].

The discussion of each type of ADAS feature within each of the four sections has two parts. First, we begin with a discussion of the functionality of a given ADAS feature. Second, we describe what is known about the effects of the ADAS feature on crash risk or behaviors related to crash risks. This can help first responders understand the benefits and possible risks of each function both with regards to their own vehicle and other vehicles.

We defer the discussion of the operational design domain of each of the ADAS features and the interaction required between the driver and the human-machine interface associated with each feature until later when we describe training (Section 5). We defer this discussion because the specifics for a given ADAS feature are particular to a given feature, make, model, year, and software update.

2.2.1 Longitudinal Control

ADAS features which provide assistance with longitudinal control are those that both warn drivers and manage vehicle speed and distance for drivers. This category includes adaptive cruise control (ACC), forward collision warning (FCW), automatic (or autonomous) emergency braking (AEB), rear automatic braking (RAB), and rear cross-traffic braking (RCTB).

2.2.1.1 Adaptive Cruise Control (ACC)

Adaptive cruise control (ACC) utilizes sensors to automatically adjust vehicle speeds through acceleration and braking in order to maintain a pre-defined distance behind a leading vehicle [25]. Research on the effects of ACC on crash risk is limited. However, the studies that do exist suggest a marginal increase in crash risk. For example, Monfort and colleagues [26] found that drivers were significantly more likely to speed (95%) while using ACC relative to manual driving (77%), a behavior well documented to be associated with higher crash risk [27]. In a more recent review of existing literature in 2025, Winkel and Cristoph [24] found that ACC was associated with an increased crash risk of 1.8% across simulation and real-world data, but an increased risk of 8% when only considering real-world data.

2.2.1.2 Forward Collision Warning (FCW)

Forward collision warning (FCW) systems monitor the road in front of a vehicle through sensors and alert the operator to a potential forward collision with a vehicle or hazard [28]. Research suggests that FCW reduces rear-end crashes by between 20-27%, and this reduction increases to 50% when FCW is paired with AEB [29] [30].

2.2.1.3 Automatic Emergency Braking (AEB)

Automatic emergency braking (AEB) utilizes sensors to detect an imminent forward collision and initiates braking independent of operator input [31]. Specifically, AEB systems measure the distance to objects and calculate time to collision (TTC), based on the current distance (range) to an obstacle, the relative speed (range rate) between the vehicle and the obstacle, and the predicted trajectory of the vehicle and obstacle [31]. Based on TTC and operator inactivity, braking is automatically applied when a collision is imminent. AEB is often activated after operator non-responsiveness to a forward collision warning [31]. A recent study assessing the efficacy of AEB systems on crash risk from 2015-2023 found AEB systems reduced rear-end collisions by 49% [32]. Another study found that AEB with pedestrian detection reduced pedestrian crash risk by 25-27% [33].

2.2.1.4 Rear Automatic Braking (RAB)

Rear automatic braking (RAB), also known as Reverse Brake Assist, aims to help drivers prevent or mitigate collisions with objects directly behind the vehicle while in reverse [34]. Specifically, RAB provides a warning through auditory, visual, and/or tactical feedback when a hazard is detected by sensors while a vehicle is in reverse [34]. If the vehicle continues in reverse after a warning, RAB then applies braking if a collision is imminent. When paired with a rear-view camera and rear parking sensors, Cicchino [29] found that RAB was associated with a reduction in crash risk by 78%, while Leslie and colleagues [30] found RAB was associated with a 82% reduction in backing crashes.

2.2.1.5 Rear Cross-Traffic Braking (RCTB)

Reverse Cross-Traffic Braking (RCTB) aims to help drivers prevent or mitigate collisions by automatically applying braking if vehicles, cyclists, or pedestrians are detected approaching from the side while the vehicle is in reverse [35], [36]. Research on the effects of RCTB in preventing collisions is scarce, given the relatively recent introduction of RCTB into vehicle fleets. However, related research on reverse cross-traffic alerting (RCTA) systems indicates that RCTA systems have significantly reduced reverse cross-traffic crashes compared with vehicles that do not have such systems installed [36] (see Section 2.2.3.2 below). This suggests that RCTB systems could reduce crashes even more given that alerts are not 100% effective.

2.2.2 Lateral Control

ADAS features which provide assistance with lateral control are those that provide warnings related to, or help manage, a vehicle's lane position. This category includes electronic stability control (ESC), lane departure warning (LDW), lane keeping assist (LKA), and lane centering assist (LCA).

2.2.2.1 Electronic Stability Control (ESC)

Electronic stability control (ESC) was introduced as an option on mass-market vehicles in 1988 and was mandated as a safety feature on all vehicles in the U.S. starting in 2012 [37]. ESC systems aim to automatically stabilize vehicles by correcting understeering or oversteering errors by effectively reducing vehicle rotation during periods of unstable driving [38]. Specifically, ESC systems use sensors to detect unstable driving per steering wheel angle, lateral acceleration and yaw rate. ESC systems use this information to assess if the vehicle dynamics are misaligned with the operator's intended steering patterns [38]. If the ESC system detects a loss of control, the ESC system applies automatic braking to one or more wheels and may reduce engine power to reduce vehicle rotation when one or more wheels are moving faster than is expected based on the steering input and turning angle [38]. ESC systems have been demonstrated to be an effective safety feature, reducing crash risk involving loss of control by 40% according to a meta-analysis [37].

2.2.2.2 Lane Departure Warning (LDW)

Lane departure warnings (LDW) aim to prevent lane departures by providing an alert to drivers when the vehicle is about to leave its lane, particularly on straightaways and highways with clear lane markings [39]. Leslie and colleagues [30] found LDW alone was associated with a 10% reduction in lane deviation crashes, while Cicchino [39] found that LDW was associated with a significantly lower rate of crashes (18%), crashes with injuries (24%), and crashes with fatalities (86%).

2.2.2.3 Lane Keeping Assist (LKA)

Lane keeping assist (LKA) aims to prevent a vehicle from committing unintended lane deviations while driving [40]. Specifically, LKA utilizes sensors to monitor lane markings, and correct lane deviations with automated steering to guide the vehicle back to the lane center when the vehicle is about to unintentionally cross the lane markings [40]. Note that LKA will not activate if the turn signal is on. LKA will also not override a driver if they deliberately turn the vehicle into another lane with some force. Leslie and colleagues [30] found that LKA paired with LDW was associated with a reduction of 12% in lane departure crashes, while de Winkel and colleagues [24] found that LKA is one of the most effective ADAS features in reducing crash risk, demonstrating a reduction in risk of 19.1%.

2.2.2.4 Lane Centering Assist (LCA)

Lane centering assist (LCA) aims to continuously provide steering input to position the vehicle in the middle of its lane [41]. LCA is similar to LKA, but it acts more proactively to continuously adjust steering to center the vehicle to the middle of the lane, rather than reactively adjusting steering to avoid a lane deviation [41]. The evidence on the effectiveness of LCA in crash prevention appears to be mixed. A study by Aukema and colleagues [42] suggests that adding LCA to LKA decreased crashes by an estimated 9%. However, a more recent study published by Cicchino [43] argues that the benefits of LCA are more likely a function of the brighter headlamps that come with an LCA system [43]. This finding is consistent with research suggesting that lane centering paired with adaptive cruise control may increase the likelihood of drivers exhibiting risky behaviors while driving, such as engaging in a secondary task [44] [45] or speeding [26]. A recent meta-analysis of confirms that that glances off road increase when partially automated driving is engaged [46].

2.2.3 Monitoring

Monitoring refers to ADAS related to detection systems that monitor: (1) the surroundings, (2) the occupants, and (3) the vehicle [24]. ADAS features related to monitoring surroundings include blind spot monitoring (BSM), and rear cross-traffic alert (RCTA). An example of monitoring occupants is a driver monitoring system (DMS). An example of monitoring the vehicle would be post-collision braking.

2.2.3.1 Blind Spot Monitoring (BSM)

Blind spot monitoring (BSM), also known as blind spot warning (BSW), alerts drivers, typically through a warning light in a side mirror, when another vehicle is detected in its blind spot on the driver's or passenger's side. In some BSW systems, an audible warning will be given if the driver activates the vehicle's turn signal [47]. Previous work suggests crash involvement rates involved in lane-change crashes were 14% in vehicles with BSM compared to those without it [47].

2.2.3.2 Rear Cross-Traffic Alert (RCTA)

Rear cross-traffic alert[2] (RCTA) aims to help drivers prevent or mitigate collisions by providing a warning if it detects vehicles, cyclists, or pedestrians approaching from the side while the vehicle is in reverse [35], [36]. Previous research suggests rear cross-traffic alert has reduced crash involvement by 22% relative to vehicles without the feature [36].

2.2.3.3 Driver Monitoring Systems (DMS)

Driver monitoring systems (DMS) utilize in-car sensors to monitor facial, eye, head and/or physiological dynamics in order to estimate a driver's attention, drowsiness, and distraction levels [48]. When estimated levels of inattention, drowsiness, or distraction deviate significantly from baseline, the DMS provides an alert to the driver to reorient to the dynamic driving task [48]. Previous data suggests DMS is associated with a 10% reduction in crash risk relative to vehicles without DMS [24].

It is important to note that DMS have, in general, thresholds for alerting drivers that are often much higher than what would be considered safe if one assumes that the driver is supposed to be continuously supervising the driving. Eyes-off-road time is an illustrative example. Naturalistic driving studies have shown that glances off-road greater than 2 seconds doubles the risk of a crash [49]. Glances longer than 3 seconds can increase the crash risk by a factor of six [50]. However, it has been reported that one commercially available DMS may not issue a warning until the driver has looked off-road for a full 10 seconds [51]. Even though DMS have been shown to reduce crashes, they could potentially reduce crashes to a greater extent if they

[2] Rear Cross-Traffic Alerts are also referred to as Reverse Cross-Traffic Alerts.

were able to warn drivers when safety-critical glances were required, thus reducing false alarms and increasing drivers' acceptance of the warning [52].

2.2.3.4 Post-collision Braking

Post-collision braking provides controlled braking pressure in response to a collision detected through existing crash-detection sensors [53]. This is designed to reduce secondary crashes. Even though speeds in a secondary collision may be slower than they were in the initial crash, a secondary collision can lead to further injuries and fatalities. The consequences can be severe in secondary collisions because many of the vehicle protection systems (airbags, seatbelt pre-tensioners, etc.) have already been deployed in the first crash. Limited research has been conducted on the safety implications of post collision braking, with an estimation that post-collision braking could reduce secondary collisions by about 30% and, importantly for LE, field fatalities by 6% [54].

2.2.4 Additional Automated Systems Unique to Law Enforcement

In addition to ADAS available on commercial cars, LE vehicles may also be equipped with features unique to LE, such as pursuit-specific calibrations, Police Perimeter Alert, and automatic license plate recognition (ALPR).

2.2.4.1 Pursuit-specific Calibrations

Pursuit-specific calibrations adjust vehicle control settings to optimize performance in pursuit scenarios. Specifically, pursuit-specific calibrations modify electronic stability control, anti-lock braking systems (ABS), and traction control [21], [22], [23]. One example that may be of assistance is calibration to avoid skidding and fishtailing during tight, fast turns.

2.2.4.2 Police Perimeter Alert

Police Perimeter Alert is an automated feature that monitors the surroundings of an LE vehicle that is stopped. The Police Perimeter Alert displays moving objects, motion trails, and associated threats to the officer on the dashboard level [21]. If a threat is detected, an auditory alert is initially administered [21]. After the alert, the doors will automatically lock, and windows will automatically go up upon escalation [21]. Example scenarios where the system is activated include unauthorized entry into a parked vehicle and the rapid movement of an individual in a high risk stop while the officer is still inside his or her vehicle.

2.2.4.3 Automatic License Plate Recognition (ALPR)

Automatic license plate recognition (ALPR), also known as automatic number plate recognition, is a tool that utilizes high-resolution cameras to capture license plate details. Mobile ALPRs are used by LE to automatically run checks on vehicles that would be impractical to perform manually. Research suggests ALPR systems demonstrate promise for improving case clearance for auto theft and robbery, but relationships between ALPR systems and case clearance become non-significant after accounting for other, contributing factors such as more license plates captured by videos or witnesses during the study window [55]. While not typically considered an ADAS feature, when equipped on a LE vehicle, ALPR has the potential to reduce secondary tasks that a LE officer may otherwise need to accomplish while driving, reducing distraction from the driving task.

2.3 Existing ADAS in Law Enforcement Vehicles

While ADAS encompasses a wide range of passive and active technologies, this report primarily focuses on ADAS features that may influence either vehicle dynamics and/or human factors during emergency operations. Based on this, we conducted a review of ADAS features available in the 2025 versions of commonly used LE vehicles by searching manufacturer websites and vehicle guides [21], [22], [23], [56]. This included the 2025 versions of the Ford Police Interceptor Utility vehicle [21], the Chevrolet Tahoe Police Pursuit vehicle (PPV) [22], and the Dodge Durango Pursuit vehicle [23]. These vehicles were selected based on previous work [17] [18]; however, we substituted the gas-powered Dodge Charger Pursuit with the Dodge Durango Pursuit following the discontinuation of the gas-powered Dodge Charger Pursuit in 2023. ADAS and LE-specific features available in 2025 LE vehicles are summarized in Table 3.

Table 3. ADAS Features Available in 2025 Law Enforcement Vehicles

ADAS Feature	Ford Police Interceptor Utility	Chevy Tahoe PPV	Dodge Durango Pursuit
Longitudinal Control			
Adaptive Cruise Control (ACC)	No	No	A
Forward Collision Warning (FCW)	S	A	A
Automatic Emergency Braking (AEB)	S	A	A
Rear Cross-Traffic Braking (RCTB)	S	A	No
Lateral Control			
Electronic Stability Control (ESC)	S	S	S
Lane Departure Warning (LDW)	No	A	A
Lane Keeping Assist (LKA)	No	A	A
Lane Centering Assist (LCA)	No	No	No
Monitoring			
Park Assist	S	S	S
Blind Spot Monitoring (BSM)	S	A	S
Rear Cross-Traffic Alert (RCTA)	S	A	S
Law Enforcement Specific Features (Non-ADAS specific)			
Pursuit Mode	S	S	No
Officer Protection Warning Systems	S	No	A
AEB Deactivation	Manual button	System Settings	System Settings
Vehicle Integration Systems**	Yes	Yes	Yes
Automated License Plate Recognition (ALPR)*	Post-Market Device		

Note: A = available, S = standard, PPV = Police Pursuit Vehicle. *ALPR are often mobile devices acquired separately from police vehicles, and do not come pre-installed. **Vehicle Integration Systems allow for custom configuration of ADAS deactivation, such as automatically disabling specific ADAS features only when a code 3 (emergency response, full lights and siren) is active.

2.4 Law Enforcement Perceptions of ADAS

Relatively few studies have been conducted to understand the perceptions of LE officers on the utility of ADAS features, the usability of ADAS interfaces, the ease of use of ADAS, their trust in ADAS, the need for ADAS training, and the use of ADAS data in crash investigations. Several of the studies that are available are reviewed below.

2.4.1 Utility of ADAS

Previous work has evaluated the actual and perceived utility of ADAS in LE vehicles, both from a systematic literature review [57] and survey-based [17] perspective. Nasr and colleagues [57] argued that ADAS features related to collision-prevention could be extremely beneficial in addressing the disproportionate crash risk experienced by LE officers, and that exploring the actual and perceived utility of ADAS for LE officers was an underexplored topic in the literature. To address this, Nasr and colleagues [57] conducted a systematic literature review to determine which ADAS features were available in modern LE vehicles, which features may be most promising to incorporate in LE vehicles in the future, and which current ADAS features would be most useful for LE officers. Both Nasr and colleagues [57] and Wozniak and colleagues [17] assessed the perception of ADAS by LE officers using online sampling methods. Nasr and colleagues' [57] survey was focused solely on the perceived utility of specific ADAS features by LE officers in order to validate findings from their literature review. Wozniak and colleagues [17] expanded this survey approach by exploring perceived utility, ease of use, training, trust, and the inter-relationships between these constructs.

First, in terms of utility, researchers in both studies found that LE officers perceived ADAS features focused on collision-avoidance (such as intersection collision avoidance, wrong way alert, and front vehicle detection systems) as more useful relative to ADAS features focused on reducing mental burden (such as highway driving assistance, lane ending detection, and traffic sign detection) [17]. These findings were largely consistent with experts' rankings of ADAS features that they considered would be most helpful for LE officers in carrying out their job duties. An exception was wrong-way alerts, which officers perceived as more useful than experts expected [57]. Further, LE officers also reported a strong preference for rear-view cameras and Bluetooth communication systems. In terms of delivering alerts from the vehicle, LE officers preferred to receive a combination of both visual and auditory modalities relative to visual or auditory alone, or vibrotactile [17]. This demonstrates that LE officers prefer cue redundancy, which has been demonstrated to be an important component of effective message delivery from a human factors perspective [58].

2.4.2 Trust of ADAS

Trust is a primary predictor of whether an LE officer will utilize, disable, or ignore ADAS [17], [59]. In a driving simulation study, LE officers reported greater trust in the ADAS-equipped vehicle relative to a manual vehicle in terms of performance (i.e., "The system provides safety"), process (i.e. "The system's mode of operation leads to unfavorable or dangerous outcomes", reverse-coded), and purpose (i.e., "The system is a reliable partner") [60]. LE officers who trusted ADAS to improve their driving safety were significantly more likely to utilize ADAS while performing a secondary non-driving related task. These LE officers also perceived ADAS as an effective method to reduce mental workload through partial automation and increased visual attention to the forward roadway through alerts [17]. While initial trust serves as a foundational building block to start using ADAS, ADAS performance over time is a crucial predictor in maintaining trust [61]. If ADAS features react in unexpected ways, such as providing alerts or braking in the absence of a hazard, a user's trust and associated use in the system will decline [61], [62]. While trust in ADAS is an important predictor of use in LE, over-trust and over-reliance also carry significant safety risks. This is particularly dangerous in situations where an LE officer's trust in the system exceeds their understandings of the actual capabilities and limitations of the system [61], [62], [63]. Overall, a calculated trust in ADAS along with reasonable expectations and a thorough understanding of its abilities and limitations is essential to reaping the safety benefits of these systems and mitigating the risks of overreliance in LE [59], [60], [61], [62].

2.4.3 ADAS Ease of Use

Ease of use is considered to be a core aspect in facilitating driver acceptance of ADAS, and is influenced by a number of factors [17], [59]. General design principles suggest that the physical interface of ADAS should be intuitive and minimize both the frequency of glances and the glance time away from the forward roadway. In a survey-based study, LE officers reported that standardization and compatibility of ADAS features with existing LE vehicles and technologies such as mobile computer terminals (MCTs) should be a top priority [17]. Related, there was significant concern among LE officers on the lack of integration of ADAS features with existing police technologies [17]. Specifically, officers were concerned with the need to interact with the MCT interface and separate ADAS interfaces simultaneously while driving. LE officers also suggested that the ability to flexibly activate and deactivate ADAS features based on situational needs was essential to trust and use of the systems [17].

Based on LE responses, researchers have made several additional recommendations including: (1) perfecting a few specific ADAS features, like collision avoidance systems, rather than incorporating a high quantity of secondary features, (2) focusing on features that improve officer safety rather than convenience, and (3) designing and integrating features in ways that do not require extensive training [17].

2.4.4 Need for ADAS Training

There is a wide gap that exists in the need for and interest in ADAS training among LE officers and the training that is currently available [17], [63], [64]. The need is not only for training on using ADAS as a driver. In one study of 66 officers investigating crashes, 80% reported a desire to receive ADAS training [63]. Despite this interest, only two out of the 66 (3%) had received formal training from a technical crash investigation school, while three (4.5%) reported receiving informal training from manufacturers or federal agencies [63]. In another training pilot study including 9 LE officers and 2 attorneys, no participants reported any prior formal ADAS training [64]. Previous work has found that training is a significant predictor of an LE officer's intention to use ADAS, in which LE officers who are more knowledgeable of ADAS are more likely to utilize the systems instead of disabling them [59]. Training is essential to helping officers gain appropriately calibrated trust in ADAS, simultaneously minimizing unwarranted skepticism and over-reliance [59], [64], [65]. Two considerable barriers to ADAS training highlighted in previous work are the competing demands of existing trainings and the potential financial burden for rural departments [66] Section 5 provides a more detailed description of ADAS training and recommendations.

2.4.5 ADAS and Crash Investigations

As mentioned above, knowledge of ADAS features can be useful for LE officers outside of their driving duties. Understanding how ADAS systems perceive their surroundings could help officers stay safe when working on the roadway, just as high-visibility clothing improves officer visibility to human drivers. Additionally, officers conducting crash investigations could benefit from understanding how ADAS may have contributed to or mitigated a crash. Nearly all of the 66 LE officers who completed a survey and 9 officers who completed a semi-structured interviewed reported that they did not consider ADAS as a routine consideration in crash investigations [63]. Specifically, only 8% of crash investigators always or usually considered ADAS, with 43% reporting never considering it during crash investigations [63]. The lack of ADAS consideration stemmed from three primary reasons: the lack of ADAS training as it relates to crashes in LE, the belief that drivers are responsible regardless of ADAS, and the difficulty in obtaining relevant ADAS data [63]. Specifically, LE officers reported skepticism that interviewing drivers about ADAS would be useful. They cited the possibility that drivers would blame system failures to deflect from human error and inattention [63]. The majority of state crash report forms also generally do not consider ADAS, in which only 11 out of 50 states have crash report forms that include checkboxes or language related to ADAS [67]. Further, LE officers cited significant barriers in ADAS data attainment. These challenges include the cost of extracting information from an event data recorder, a lack of standardization across manufacturers, an inability to determine ADAS equipage based on VIN, and the legal requirements needed for access [63]. Researchers argue that despite these barriers, attaining ADAS data on crashes is essential for understanding the causal and contextual factors related to crashes, as well as building real-world evidence on the potential safety benefits of ADAS among the public [63].

2.5 Driving Challenges Facing First Responders

There are two major challenges facing first responders while driving vehicles equipped with advanced driving assistance systems outside of tactical situations. They include the potential for increases in drowsiness and workload.

2.5.1 Drowsy Driving: A Critical Concern among First Responders

Drowsy driving, the act of driving while so tired that it is difficult to keep one's eyes open, is one of the most common risky driving behaviors with a lifetime prevalence of 62% [68]. Previous research suggests 24 hours of wakefulness is associated with a greater degree of overall driving impairment than a 0.05% blood alcohol concentration [69]. Drowsy driving carries significant consequences to driver safety, with the AAA Foundation estimating sleepiness is a factor in 21% of all fatal motor vehicle crashes, and 13% of motor vehicle crashes requiring hospitalization [70].

Previous work suggests poor sleep quality is extremely prevalent among first responders. One meta-analysis found 51% of LE officers experience poor sleep quality [71]. More recent studies have found an even higher prevalence of poor sleep quality among LE officers, with a prevalence between 70 to 77.4 percent [72], [73]. Sleep disorders are also twice as prevalent among LE officers relative to the general population [74]. In one study of almost 5,000 state and local LE officers in the United States and Canada, just over 40 percent of officers had at least one sleep disorder [75]. Similar rates of sleep disorders were found among U.S. firefighters [76]. In one large scale study including nearly 7,000 U.S. firefighters, 37.2% of the sample screened positive for at least one sleep disorder [76]. Another study among EMS workers found 50% reported sleeping only six hours every 24 hours, and over 50% of workers reported experiencing poor sleep quality [77].

These concerning trends translate to a high rate of self-reported drowsy driving and increased crash risk among first responders. Approximately 46% of LE officers report falling asleep while driving, with 26.1% reporting falling asleep while driving once or twice a month [74]. LE officers working night shifts are particularly vulnerable to fatigue-related crashes, with one simulator study finding night-shift LE officers were 2.5 times more likely to experience a collision relative to day-shift LE officers [72], [78]. Firefighters who screened positive for a sleep disorder are 2.4 times more likely to report falling asleep while driving and twice as likely to be involved in motor vehicle crash relative to firefighters without a sleep disorder [76].

Considering the risk of drowsy driving among first responders, ADAS may be very helpful in both alerting the driver to pay attention to the forward roadway and manually intervening in the absence of a driver response to prevent a collision. Driver monitoring systems (DMS) can track physical and mental states of the operator by monitoring hand placement, eye movements, and facial dynamics, and may alert a fatigued driver with auditory and/or haptic feedback to stay awake or pull over for safety [79]. One study found that a DMS warning system was associated with a 66% reduction in fatigue events relative to no feedback being provided [79]. Lateral control ADAS features like LDW, LKA, and LCA may substantially mitigate the risk of fatigue-related run-off-the-road crashes and side angle crashes by alerting the driver of potential lane deviations and by actively intervening to keep the vehicle in the lane [39], [40], [41]. Longitudinal control ADAS features like FCW and AEB may substantially reduce fatigue-related rear end crashes by alerting the driver of a potential collision and activate braking to prevent it [29].

Despite this potential, ADAS features could potentially also increase drowsiness in some scenarios. In one study by Flynn-Evan and colleagues [80], participants completed two sessions in a driving simulator, one in which the vehicle was controlled manually and one which the vehicle was controlled by the automation. In the automated session, the driver was instructed to supervise the automation throughout the drive. Various measures were recorded throughout both the manual and automated drives. The researchers found that the participants said that they felt drowsier during the automated drive session relative to the manual session [80]. This was validated by physiological measures, in which a measurement of brain electrical activity indicated that participants had more involuntary transitions into sleep during the automated session relative to manual session. Finally, reaction times were slower and attentional lapses were more frequent in the automated drive session relative to the manual session [80]. This can be yet another reason that vehicles equipped with Level 2 automation may not necessarily be safer than vehicles which are manually driven [43].

2.5.2 Cognitive Load Management While Driving Among First Responders

Cognitive theories of information processing suggest that human attention is a limited resource, and performance degrades when an individual attempts to interleave the completion of two or more tasks with similar behavioral requirements [81], [82], [83], [84]. First responders often experience high workloads while driving due to the unique demands of the job. During normal patrol conditions, LE officers often must complete a secondary non-driving related task, such as engaging with an MCT, while driving [85]. This introduces a high amount of cognitive load on the LE driver due to the dual demands of driving and MCT engagement on both visual resources and procedural resources [81]. Under emergency and pursuit conditions, the added stress and increased driving difficulty introduce greater cognitive requirements, increasing the risk of cognitive overload [86], [87]. Further, studies show that EMS students conduct anticipatory medical planning during emergency driving, adding additional cognitive load and risk [88].

Based on the unique demands on first responders while driving, ADAS may be even more effective in crash prevention compared to the general population [60]. ADAS warnings like FCW and LDW may help reorient LE drivers to focus on the driving task during periods of high distraction due to secondary non-driving related tasks [60]. Longitudinal and lateral intervention systems like AEB and LKA may also prevent distraction-related crashes for first responders, even in the absence of a driver responding appropriately to warnings [31], [33], [40]. Research suggests that ADAS, specifically AEB, FCW, and BSM, do effectively reduce perceived workload relative to manual operations in normal driving conditions [60].

On the other hand, there is a concern that increased ADAS adoption and use among first responders could lead to cognitive underload and over-reliance [63], [89]. Cognitive underload refers to the suboptimal attentional state in which a driver is not sufficiently alert and engaged to perform to the best of their abilities [90]. The negative effects of over-reliance may include increased multitasking while driving [62], hands and feet disengagement [62], reduced situational awareness [61], and neglecting visual mirror checks [63]. While the concerns about cognitive underload and over-reliance have been supported by previous work [91], [92], a more robust evaluation of the literature suggests mixed evidence [46]. One meta-analysis exploring the effects of partial automation on mental workload, visual behavior, and engagement across 41 studies found no significant differences in mental workload across manual and partially automated driving [46]. Yet, researchers also found that participants were more likely to glance away from the forward roadway, and engage in nondriving-related secondary tasks during partially automated driving relative to manual [46]. This suggests that the safety benefits of ADAS may be somewhat offset among civilians by an increased tendency to drive distracted [46].

3 Potential Benefits and Pitfalls of ADAS for First Responders

Above, we described the known benefits and pitfalls of ADAS features installed on first responder vehicles that had been studied. In this section, we turn to the potential benefits and pitfalls of said systems. First, experimental studies assessing the benefits and tactical limitations of specific ADAS features are described in Section 3.1. Second, the potential benefits of ADAS related to crash risk with implications for LE during routine driving are discussed in Section 3.2. This topic is important because between 60 to 81 percent of LE crashes occur during routine driving [11], [12]. The potential pitfalls, however, are two-fold. On the one hand, there is the impact of the ADAS features on the driver in routine driving when the intended vehicle function, operational design domain (ODD), and operation of the HMI are not well understood (Section 3.3). These systems require that the LE officers have an almost instantaneous understanding of all three domains, one that agencies will need to consider when purchasing vehicles with ADAS features (Section 4) and when training LE officers (Section 5). On the other hand, even if the functionality, ODD, and HMI are well understood, it is still the case that in high stress scenarios the ADAS features can behave in ways that officers might not expect (Sections 3.4 and 3.5).

3.1 Current Literature on ADAS Implications for First Responders

In Section 2.4, we evaluated how LE officers perceive ADAS. Second, in Section 2.5, we detailed two of the greatest safety risks to first responders (drowsy driving and distracted driving) and described how ADAS could help address this risk. In this section, we review research that has directly assessed how specific ADAS features, or combinations of features, influence driving performance and maneuver execution in first responders.

3.1.1 The Influence of ADAS on Driving Behavior Among Law Enforcement

As briefly noted in Section 2.5.2, Shahini and colleagues [60] explored the impact of forward collision warning (FCW), automatic emergency braking (AEB), and blind spot monitoring (BSM) on LE officers' driving performance, cognitive workload, and trust through a driving simulation study. Researchers utilized a within-subjects design to assess four variables: ADAS activation (active vs. inactive), driving scenario (routine patrol vs. pursuit), secondary task engagement (license plate checking task or no secondary task), and hazard condition (braking lead vehicle, vehicle in a blind spot while changing lane, both hazards) [60].

Researchers found several interesting and nuanced results. In terms of performance, researchers found that there was a significantly larger minimum time to collision (TTC) with ADAS activated relative to manual driving, across both the braking lead vehicle and dual hazard (blind spot and braking lead vehicle) scenarios [60]. This indicates that ADAS provided officers with more time to detect and respond to a hazard, relative to manual driving. Further, braking intensity (maximum longitudinal deceleration) was significantly higher with ADAS active in the dual-hazard condition relative to manual driving [60]. These differences were not consistent across normal and pursuit conditions. Specifically, there were no significant differences in TTC across ADAS and manual driving in pursuit scenarios, suggesting limited applicability during these high-stress conditions [60]. This mirrored findings in lateral acceleration as well, in which ADAS was only associated with greater lateral vehicle stability in normal scenarios, but not pursuit scenarios [60]. Researchers hypothesized these differences stem from LE drivers experiencing cognitive overload during pursuit scenarios, in which alerts like FCW and BSW compete for visual and auditory resources that are actively engaged by focusing on the forward roadway and radio communications [60].

However, FCW and BSW were demonstrated to mitigate the increased subjective cognitive workload when officers engaged in a non-driving related task in normal scenarios. Further, there were no differences in pupil dilation, a measure of cognitive effort, across manual driving and ADAS active conditions across all scenarios [60]. In terms of trust, LE officers reported significantly higher trust (in terms of vehicle safety) with ADAS active relative to manual driving, viewing the systems as a reliable partner [60]. Importantly, ADAS alerts were 100% accurate in the simulated driving conditions [60], and the effects of false-positives (alerts implemented incorrectly) and false-negatives (missed alerts when situationally appropriate) would likely negatively influence trust [61].

3.1.2 The Influence of Electronic Stability Control (ESC) on Precision Immobilization Technique (PIT) Maneuvers

The Precision Immobilization Technique (PIT) is a maneuver used by LE officers to disable a fleeing vehicle, as well as in protective operations to remove aggressive vehicles from convoys [5]. During a PIT, a pursuing LE vehicle applies lateral contact to the left or right back end of a target vehicle, causing the target vehicle to lose control and spin out [5]. Performing a PIT maneuver carries considerable risk to LE, occupants of the fleeing vehicle, other road users, and pedestrians. It is generally considered appropriate in only a few specific situations (see Section 3.5). Several studies have explored the potential influence of ESC on the dynamics of PIT maneuvers.

In a study conducted by Zhou and colleagues [93], researchers utilized models to predict the vehicle dynamics of the pursuer's and target vehicle. With respect to the pursuer's vehicle, simulation was used to provide guidelines for the effective execution of the PIT maneuver. It was demonstrated in the simulations that a reasonably large lateral clearance and sufficiently fast preimpact steering action of the pursuer's vehicle (the LE vehicle) are more likely to lead to an effective PIT maneuver. What happens after the PIT maneuver to the target vehicle depends on whether active safety systems such as electronic stability control (ESC) systems are installed. If they are installed and active, the responses of the target vehicle equipped with ESC can come as a surprise to the LE officer and make the PIT maneuver less effective.

The first study to explore this in a field study was conducted by Burleson and colleagues in 2015 [19]. In this study, researchers aimed to characterize PIT effectiveness and safety in a scenario where a pursuing vehicle, not equipped with ESC, attempted to perform a PIT on a target vehicle that either was equipped with ESC or was not at various speeds (25, 30, 35, 40, and 45 mph) [19]. Supplementary runs were also conducted to assess the influence of the target vehicle's ESC being set to performance mode, as well as also having the driver of the target car attempt to maneuver out of a PIT [19]. Researchers found that the target vehicle with ESC exhibited greater secondary impacts and rotating unpredictability after the PIT relative to the target vehicle without ESC [19][3]. The severity of secondary impacts on the pursuing vehicle varied based on speed, with greater impact at higher speeds [19]. Further, the target vehicle with ESC exhibited inconsistent vehicle dynamics in response to a PIT in terms of rotation and centerline deviation at higher speeds relative to the target vehicle without ESC [19]. Finally, a few exploratory runs in which the pursuit vehicle was equipped with ESC suggested that ESC may diminish the ability of the pursuit vehicle to perform a PIT by counteracting the steering and turn angle required to conduct the maneuver.

[3] Note that this is consistent with the simulations of Zhou and colleagues [93].

A similar study was conducted in 2017, in which researchers explored the effects of ESC during a PIT on both the pursuit and target vehicle dynamics [20]. Researchers found that operators of pursuit vehicles needed to administer greater steering input, more throttle, and heavier braking when executing the PIT to a target vehicle with ESC relative to a target vehicle without ESC [20]. Further, target vehicles equipped with ESC rotated less relative to target vehicles without ESC and came to a stop closer to the pursuit vehicle. These dynamics raise the risk of secondary impacts on the pursuit vehicle and of non-crash risks when performing the maneuver (e.g., the LE officer being in the line-of-fire of a fleeing suspect) [20]. Importantly, PIT success rates varied dramatically across vehicle makes and models equipped with ESC, suggesting the few studies done to characterize PIT performance on target vehicles with ESC may not generalize across vehicles available to consumers [20].

3.1.3 The Influence of Curve Speed Warning Systems on Crash Risk for Fire Tankers

Vehicle crashes are the third leading cause of on-duty death in firefighters [94]. Among vehicles operated by firefighters, fire tankers are particularly vulnerable to rollover crashes due to a high center of gravity [94]. To address this issue, researchers conducted a driving simulation study to assess the potential influence of curve speed warning systems (CSWS) on crash risk for fire tankers [94][4]. Researchers utilized three groups of dependent variables to assess outcomes: driving performance, safety outcomes, and system acceptance [94]. From a driving performance standpoint, researchers found that the curve speed warning system (CSWS) did not have a significant effect on the average or maximum speed for the whole route [94]. The CSWS did significantly reduce approach and entry speeds at the sharpest curves (turn radius < 100 meters) but were associated with a minor increase in speeds at less sharp curves (turn radius > 100 meters). CSWS also led to a reduction of severe braking around curves in favor of mild and moderate braking. CSWS also had a positive impact on several safety measures. Specifically, CSWS reduced the maximum speed into sharp curves, and the total distance driven between 5% and 10% above the speed limit around sharp curves. However, CSWS did not have a statistically significant effect on total distance driven between 0% and 5% above the speed limit or greater than 10% above the speed limit around sharp curves. Finally, drivers had very positive perceptions of the CSWS after use, rating it as useful and satisfying [94]. These findings may be applicable to large tactical vehicles used by LE in certain scenarios.

[4] Note that CSWS are not available on the three pursuit vehicles included in Table 3 which is why this ADAS feature was not included in Section 2.1.

3.2 Benefits for Law Enforcement Patrol during Routine and Non-emergency Conditions

Several ADAS features which have been demonstrated to reduce crash risk for civilians are likely to offer similar benefits in LE vehicles during routine patrol duties, as well as firefighters and EMS personnel during non-emergency driving. Four types of crashes are most likely to see benefits: rear-end crashes, angle and side-swipe crashes, crashes while backing up, and run-off-the-road crashes.

3.2.1 Rear-end Crashes

Research suggests that rear-end crashes make up somewhere between 13-37% of total crashes involving LE vehicles [9], [12]. ADAS technologies focused on longitudinal control, specifically FCW and AEB, may substantially mitigate crash risk in these areas [29]. FCW may alert a distracted or fatigued officer to abrupt stops by a lead vehicle, while AEB would likely be initiated automatically to prevent rear-end crashes. Driver monitoring systems (DMS) may mitigate rear-end crashes caused by fatigued or distraction by alerting drivers of their state, encouraging reorientation to the forward roadway and increased situational awareness [48]. ACC may be theoretically useful in mitigating rear-end crashes by automatically keeping a specific following distance, but ACC may also lead to over-reliance [43]. Further, no evidence to date suggests that ACC mitigates rear-end crashes among the general population, with the best available evidence finding ACC marginally increases crash risk [24].

3.2.2 Angle and Side-swipe Crashes

Research suggests that angle and side-swipe crashes comprise between 27-55% of crashes involving LE vehicles [9], [12]. Angle crashes can potentially be prevented by the introduction of intersection collision avoidance systems into new vehicles [95], [96]. These systems have sensors that can detect an object's speed, location, and potential risk of a collision from a lateral direction [95], [96].

Additionally, a number of lateral control systems, specifically BSM, LDW, and LKA can reduce side-swipe crashes, either when an emergency vehicle changes into another driver's lane or another driver changes into an emergency vehicle's lane. Specifically, previous work suggests lane-change crashes were 14% lower in vehicles with BSM compared to those without it [47]. LDW has also demonstrated efficacy in reducing crashes, specifically reducing fatalities by 86% [39]. The reductions in injuries was less dramatic (24%) [39].

DMS may mitigate angle and side-swipe crashes caused by fatigue or distraction by alerting drivers of their state, encouraging reorientation to the forward roadway and increased situational awareness [48].

3.2.3 Crashes while Backing Up

LE driver training documents suggest that 50% of collisions that occur during non-emergency LE driving are while the vehicle is in reverse [97]. While crashes that occur from backing up are less likely to result in injury or death relative to other types of crashes, they do account for a large percentage of crash repair costs for fire and EMS vehicles [16]. Previous research suggests that back-up cameras, parking sensors, rear cross-traffic alert, rear cross-traffic braking, and rear automatic braking may substantially mitigate crash risk while reversing [36], [98].

3.2.4 Run-off-the-road Crashes

In the period between 1997 and 2007, run-off-the-road (ROR) crashes accounted for about 70% of all fatal, single-vehicle crashes on the road [99]. In the period between 2019 and 2023 they accounted for 62% of all fatal, single vehicle crashes[5]. One study shows that likely leading causes of single-vehicle ROR crashes were inattention, fatigue, and driving under time pressure [100]. As noted above, drowsy driving itself has been estimated to be involved in 21% of fatal crashes between 2009 and 2013 [70] and 17.6% of fatal crashes between 2017 and 2021 [101]. Considering that drowsiness and inattention are leading causes of ROR crashes, DMS may mitigate a disproportionate share of ROR crashes by alerting drivers of their state, encouraging reorientation to the forward roadway and increased situational awareness [102]. Other factors influencing ROR crashes are infrastructure design, speed, and environmental conditions. ROR crashes are also a significant concern for heavy emergency vehicles [16]. Specifically, two-thirds of all fatal fire tanker crashes are a result of the vehicle's right-side wheels leaving the road surface [16]. Several ADAS features may effectively prevent ROR crashes in emergency vehicles when these other factors are operative. LDW may alert the driver to a potential lane deviation [39], while LCA and LKA may actively mitigate lateral lane deviations by providing counteracting torque [40], [41]. Advance curve speed warning systems have already been discussed (Section 3.1.3) and may prove especially useful, not only for alert and attentive drivers, but also for drivers who are not used to applying the necessary braking force with sufficient time to be reduce speed appropriately in heavy vehicles like ambulances, various types of fire trucks, and LE tactical vehicles [94]. This could be particularly beneficial for drivers who often drive other, lighter vehicles in addition to these heavier vehicles.

3.3 Routine Driving Pitfalls: Function, ODD, and Human-Machine Interface of ADAS Features

In the above section, we described the potential benefits of ADAS for first responders based on data from studies not directly addressing first responder crashes. In this section we describe

[5] Analysis done using FARS data.

the potential pitfalls during routine driving of ADAS features. First, we detail the functionality of two ADAS features, LCA and ACC. Second, we describe the operational design domain of each feature in more detail for a particular vehicle make and model. The ODD defines the boundaries in which a specific ADAS feature will work as intended. For example, an LCA feature that depends on cameras alone can only work if the cameras are not obscured by dirt or mud. The ODD of a particular ADAS feature is one of the most important aspects about a particular feature of which first responders need to be aware. Attempting to operate an ADAS feature outside of its ODD can endanger the driver because the system is not designed to handle scenarios outside of the ODD. Third, we describe operational requirements of the human-machine interface (HMI) that control ADAS engagement. These specifics, like knowledge of the ODD, are important for training.

As noted above, the functionality, ODD, and HMI are discussed for only two ADAS features, FCW and ACC. All three vehicles listed in Table 3 have FCW as standard or available. While it is the case that the only one of the vehicles listed in Table 3 has ACC available, ACC is a popular ADAS system that is increasingly being incorporated into commercially available vehicles [25]. Since the functionality, ODD, and HMI vary with each feature as it is implemented in a particular make, model and year, we needed to pick a specific example. We chose the 2025 Chevrolet Tahoe/Suburban since information is available on both FCW and ACC in the owner's manual [103].

3.3.1 Forward Collision Warning (FCW)

As noted immediately above, the 2025 Chevrolet Tahoe has an FCW system (referred to as a Forward Collision Alert, or FCA, system). All discussion below refers to material that was retrieved from the owner's manual for that system.

3.3.1.1 Functionality

The functionality of the Forward Collision Alert is explained in the owner's manual. Briefly, the function of the FCA is to help the driver "avoid or reduce the harm caused by front-end crashes". How the driver can access this functionality is discussed in the section on the HMI of the FCA (Section 3.3.1.3).

3.3.1.2 Operational Design Domain

The owner's manual states that FCA detects vehicles within a distance of approximately 60 m (197 ft) and operates at speeds above 8 km/h (5 mph). If the vehicle has ACC, it can detect vehicles at distances of approximately 110 m (360 ft) and can operate at all speeds. However, as noted above, there are several limitations to ACC which also apply to FCA. Moreover, the ODD has the following limitations of which the driver needs to be aware:

- FCA is a warning system and does not apply the brakes. When approaching a slower moving or stopped vehicle ahead too rapidly, or when following a vehicle too closely, FCA may not provide a warning with enough time to help avoid a crash.
- FCA may not detect a vehicle ahead if the FCA sensor is blocked by dirt, snow, or ice, or if the windshield is damaged, not cleaned or in proper condition. The driver needs to keep the windshield, headlamps, and FCA sensors clean and in good repair.
- FCA may not detect a vehicle ahead even if the sensors are not blocked in conditions that can limit visibility such as fog, rain, or snow.
- FCA may not detect a vehicle on winding or hilly roads.
- FCA may not provide any warning at all. FCA does not warn of pedestrians, animals, signs, guardrails, bridges, construction barrels, or other objects. The driver should be ready to take action and apply the brakes.

The driver needs to be acutely aware of these scenarios.

3.3.1.3 Human-Machine Interface

The human-machine interface, even for something as simple as an FCW system, can be complicated. There are three aspects to the HMI. First, there is what the driver needs to do to configure the system. In this case, the driver needs to set the warning time to near, medium or far. The driver also needs to know where on the HMI to control these settings. This control is on the steering wheel on the 2025 Tahoe.

Second, the driver needs to understand what, if any, effects the change in the FCA setting has on other settings. In this case, the driver needs to understand that changing the FCW warning also changes the Tailgating Alert Warning. And, if the vehicle is equipped with ACC, changing the FCW setting automatically changes the ACC following gap setting.

Finally, the driver needs to understand the various warnings that are provided and the actions that are taken when the FCW warning is activated:

- The red FCA display will flash on the windshield.
- Eight rapid high-pitched beeps will sound from the front, or both sides of the Safety Alert Seat will pulse five times.
- The brake system may prepare for driver braking to occur more rapidly which can cause a brief, mild deceleration. The driver needs to continue to apply the brake pedal as needed.
- Finally, FCA may provide unnecessary alerts for turning vehicles, vehicles in other lanes, objects that are not vehicles, or shadows.

It is an open question of whether the brief, mild deceleration might prompt the driver to think that the vehicle ahead was slowing down and no more braking was needed. As for unnecessary alerts, a recent IIHS study found that some 94% of FCW systems that are installed on vehicles are activated, indicating that false alerts are not perceived by most drivers as a problem [104].

3.3.2 Adaptive Cruise Control (ACC)

As noted above, the 2025 Chevrolet Tahoe [103] has an ACC system. All discussion below refers to materials that were retrieved from the owner's manual for that system.

3.3.2.1 Functionality

The functionality of ACC is explained in the owner's manual. Briefly, the function of the ACC is to "reduce the need for you [the driver] to frequently brake and accelerate, especially when used on expressways, freeways, and interstate highways. When used on other roads, you may need to take over the control of braking or acceleration more often.". How a driver can turn on this functionality is discussed in the section on the HMI of the ACC (Section 3.3.2.3).

3.3.2.2 Operational Design Domain (ODD)

As noted above, the ODD defines the conditions under which a particular driving automation feature works. Paraphrasing the owner's manual, the driver needs to be aware when certain conditions exist and take necessary actions [103]:

- ACC has limited braking ability and may not have time to slow the vehicle down enough to avoid a collision with another vehicle you are following. This can occur when vehicles suddenly slow or stop ahead or enter your lane. Thus, the driver must always be prepared to brake quickly.
- ACC must not be used on winding and hilly roads or when the sensors are blocked by snow, ice, or dirt. The system may not detect a vehicle ahead. The driver should keep the entire front of the vehicle clean.
- ACC performance is limited when visibility is poor, even if the sensors are not blocked, due to rain, snow, fog, dirt, insect residue, or dust; when other foreign objects between the sensor and a target obscure the camera and/or radar; or when the vehicle in front or oncoming traffic causes additional environmental obstructions, such as road spray. The driver needs to pay attention to these conditions.
- The driver should not use ACC on slippery roads where fast changes in tire traction can cause excessive wheel slip.

The driver needs to be aware of these limitations.

3.3.2.3 Human-Machine Interface (HMI)

The same three aspects that defined the FCA HMI define the ACC HMI. However, the specifics differ. First, the driver must set various features of the ACC using the human-machine interface.

Initially, the driver must select the following distance gap and know where on the HMI to set that gap. Once that is set, if the driver is moving and wants to activate ACC, he or she needs to:

- Turn ACC on,
- Accelerate to the desired speed,
- Briefly press the SET button and release it,
- Remove his or her foot from the accelerator.

The driver needs to follow additional steps while driving to increase speed while the ACC is at a set speed:

- The driver can use the accelerator pedal to accelerate to the desired higher cruise speed. Briefly, this requires pressing and releasing the button down to –SET and releasing the accelerator pedal. The vehicle will then cruise at the higher set speed.
- When the accelerator pedal is pressed, ACC will not brake because the driver is overriding ACC. While overridden, the ACC indicator light is lit blue on the instrument cluster.
- The driver can press and hold the button up to +RES until the desired set speed is displayed, then release it.
- To increase the vehicle speed in smaller increments, the driver must briefly press the button up to +RES and release it. For each press, the vehicle speed increases by 1 mph.
- To increase the vehicle speed in larger increments, the driver must press and hold the button up to +RES. While holding up to +RES, the vehicle speed increases to the next 5 mph mark on the speedometer, then continues to increase by 5 mph while holding the button.

The driver also needs to know what steps must be taken to increase the set speed while stopped or to reduce speed while ACC is activated.

Additionally, the driver must understand what changes occur to other settings if ACC settings are changed. The owner's manual states:

- Changing the following gap setting automatically changes the alert timing sensitivity (Far, Medium, or Near) for the Forward Collision Alert (FCA) feature.

Finally, the driver needs to understand the information about the status of the ACC on the HMI, the various warnings that are provided by the ACC (but not LCA), and what the driver needs to do if a warning is activated.

- **ACC Activation Status**. First, and perhaps most importantly, the driver should always check the cruise control indicator on the instrument cluster to determine which mode cruise control is in before using the feature. If ACC is not active, the vehicle will not automatically brake for other vehicles, which could cause a crash if the brakes are not applied manually.

- **Resume Notifications (Lead Stopped Vehicle Pulls Away)**. Unlike FCA, which only monitors for danger, ACC provides a proactive alert when a stopped lead vehicle moves away.
- **ACC Override Alert.** ACC provides a specific visual status warning when the driver manually accelerates over the set speed, which disables ACC braking.
- **ACC on Sharp Curves**. ACC may operate differently in a sharp curve. It may briefly reduce the vehicle speed if entering a curve that is too sharp. If equipped, the curve speed control indicator light may illuminate green when ACC detects a sharp curve in the road ahead and is actively controlling the vehicle speed. ACC may automatically decrease the vehicle speed while entering the curve. ACC may accelerate when exiting the curve, but it will not exceed the set speed.

3.4 Pitfalls for First Responders: AEB Sensor Malfunctions

A key concern for first responders is ADAS-equipped passenger vehicles failing to recognize crash event scenes, and subsequently colliding with first responders at the scene or the crash scene itself [105]. This was highlighted by complaints submitted to the National Highway Traffic Safety Administration (NHTSA). In response, NHTSA opened a formal investigation in 2021 after identifying at least 11 instances of ADAS-equipped vehicles striking vehicles involved in first responder scenes [105]. Most incidents occurred at night, and were confirmed to have engaged either both ACC and LCA, or ACC only [105].

Relatedly, a study assessing AEB function at night across a number of makes and models found certain vehicles demonstrated difficulty in detecting dummies dressed in reflective jackets or clothing with reflective strips [106]. Specifically, researchers found the 2023 model versions of the Honda CR-V and Mazda CX-5 did not activate AEB in response to approaching pedestrian dummies dressed with clothing containing reflective strips at 25 mph across three lighting conditions (none, 10 lux, 20 lux) [106]. The Honda CR-V's AEB also did not activate across the three conditions when dummies were dressed with reflective jackets, while the Mazda CX-5 exhibited inconsistent AEB activation to reflective jackets (53% with no road illumination, 58% at 10 lux, and 62% at 20 lux) [106]. When tested, the Subaru Forester did perform markedly better, demonstrating AEB activation in response to dummies dressed with reflective jackets and clothing with reflective strips across lighting conditions with 100% accuracy, with the exception of AEB activation occurring 82% of the time in response to clothing with reflective strips in the 10 lux condition [106]. While researchers did not theorize on the root cause of the underlying differences across makes and models, the differences in performance were concerning.

Another study conducted by AAA in 2025 assessed the performance of four different vehicles (2025 Toyota Camry, 2025 Tesla Model 3, 2024 Honda Accord, and the 2025 Chevrolet Malibu) with a perpendicular crossing scenario with vehicles traveling at approximately 25 miles per hour [107]. The crossing scenario was repeated 10 times at night, 5 times with the pedestrian wearing low visibility clothing and 5 times with the pedestrian wearing high visibility clothing. In each scenario, for each vehicle, the researchers recorded the number of times out of 5 that FCW activated, AEB activated, and the pedestrian target was avoided. There were considerable differences among the four vehicles for nighttime performance (Table 4).

Table 4. Night-time Pedestrian-automatic Emergency Braking Performance [107]

	Standard Clothing			High-Visibility Clothing		
Vehicle Model	**FCW Activation**	**AEB Activation**	**Avoided Pedestrian Target**	**FCW Activation**	**AEB Activation**	**Avoided Pedestrian Target**
Honda Accord (2024)	3/5	3/5	2/5	0/5	0/5	0/5
Toyota Camry (2025)	5/5	5/5	5/5	5/5	5/5	5/5
Chevrolet Malibu (2025)	4/5	4/5	1/5	5/5	5/5	3/5
Tesla Model 3 (2025)	5/5	5/5	4/5	5/5	5/5	5/5

Note: AEB = automatic emergency brake, FCW = forward collision warning

While several vehicles' automatic emergency braking systems performed better when the dummy pedestrian was fitted with high-visibility clothing, success was not universal. The 2024 Honda Accord performed markedly worse under the high-visibility clothing condition relative to standard clothing [107]. Together, these studies suggest that AEB systems differ considerably in pedestrian detection, especially under conditions in which pedestrian dummies are fitted with reflective clothing. This is a significant deviation from braking performance in human operators, in which high-visibility clothing is associated with substantial benefits to pedestrian detection due to its salience [108].

3.5 Potential Tactical Driving Pitfalls for ADAS-equipped Vehicles

There are a number of tactical driving maneuvers used by LE personnel with which ADAS features may unintentionally interfere. Previous field studies have demonstrated that electronic stability control (ESC) interferes with the precision immobilization technique (PIT), making the technique more unpredictable and less safe [19], [20], [93]. Yet, similar studies have not been conducted with other ADAS, despite the possibility that active collision avoidance systems may interfere with several tactical driving maneuvers. LE tactical driving maneuvers found in previous work [97], [109], [110] are summarized in Section 3.5.1. The potential interference between specific ADAS features and tactical driving maneuvers are summarized in Section 3.5.2.

3.5.1 Law Enforcement Tactical Driving Maneuvers

Tactical driving maneuvers are described below, some of which are limited to certain scenarios. In Section 3.5.2, ADAS limitations will be considered only in those scenarios which are permitted.

3.5.1.1 Vehicular Pursuits

A vehicular pursuit is an active attempt by an LE officer to apprehend a driver or occupant of a moving vehicle who has been signaled by emergency lights and siren, but takes evasive action to elude LE [109]. According to a report authored by the Department of Justice (DOJ) and the Police Executive Research Forum (PERF), pursuits are only appropriate if the fleeing vehicle occupant is a suspect of a violent crime and poses an immediate threat to public safety [109].

3.5.1.2 Boxing-In

Boxing-in refers to using LE vehicles to physically surround a suspect vehicle that is either stopped or nearly stopped to prevent the vehicle from fleeing [109]. According to a report authored by the DOJ and PERF, boxing-in is not appropriate as a tactic to stop a fleeing vehicle. Agencies may consider allowing LE officers to box-in stopped or nearly stopped vehicles [109].

3.5.1.3 Precision Immobilization Technique (PIT)

A precision immobilization technique (PIT) involves using LE vehicles to apply lateral pressure to the left or right side of a rear of a fleeing vehicle to cause the vehicle to spin out [109]. According to a report authored by the DOJ and PERF, a PIT maneuver is only appropriate if the driver is trained in PIT maneuvers, all alternative options have been exhausted in the pursuit, back-up is present, and supervisor approval is given [109].

3.5.1.4 Moving Roadblocks

Moving roadblocks involve using multiple LE vehicles to contain a suspect vehicle while in motion (e.g., rolling blocks) [97]. According to a guide published by the International Association of Directors of Law Enforcement Standards and Training (IADLEST), moving roadblocks are not appropriate as a tactic to stop a fleeing vehicle. Agencies may consider stationary road blocks in order to pin a stationary vehicle in place [97].

3.5.1.5 Tactical Backing

Tactical backing refers to rapid maneuvering in reverse, often involving the "Palm Method" for steering while looking through the rear window [97]. According to a guide published by

IADLEST, backing up should largely be avoided if possible. Backing up should also occur in a straight line if possible [97].

3.5.1.6 Evasive Steering

Evasive steering refers to a vehicle making a sudden lane change to avoid an obstacle (pedestrian, stopped car) by turning the wheel 1/2 rotation and then returning it [97]. Evasive steering may be required in high-risk situations. According to a guide published by IADLEST, the driver should focus on visualizing the path-of-travel during evasive steering [97].

3.5.1.7 Ramming

Ramming involves deliberate physical contact between the LE vehicle and suspect vehicle to force a stop [109]. According to a report authored by the DOJ and PERF, ramming is generally classified as deadly force, and is only appropriate in instances in which lethal force is authorized to prevent serious injury or fatalities [109].

3.5.1.8 Channelization

Channelization involves using fixed objects to direct a moving vehicle toward a specific path [109]. According to a report authored by the DOJ and PERF, channelization that utilizes LE vehicles to forcibly stop a fleeing vehicle is not an appropriate tactic [97].

3.5.1.9 Emergency Escorts

Emergency escorts involve leading motorcades, emergency vehicles, or civilian vehicles to a predetermined destination [97]. According to a guide published by IADLEST, emergency escorts at high speeds are considered as dangerous as pursuits [97]. Motorists often assume the road is clear after the first emergency vehicle, causing collisions [97].

3.5.1.10 Protective Details

Protective details involve operations designed to protect visiting dignitaries or high-profile individuals [110]. Guidelines on protective details are considered sensitive and are generally restricted for operational security [110].

3.5.2 ADAS Features and Potential Tactical Interference

This section details how each of the ADAS features may be of concern in a particular tactical maneuver. This section is organized around ADAS features and how each may interfere with one or more of the above maneuvers. To date, only ESC during a PIT maneuver [19], [20], [93], as well as FCW, BSM, and AEB during pursuit scenarios [60], have been studied by researchers in the field of ADAS and tactical interference. Beyond this, hypothesized interference between specific ADAS and tactical driving maneuvers are based on our understanding of requirements of tactical maneuvers, as well as ADAS functionality, ODD, and HMI interactions. Table 5 summarizes potential interactions between active ADAS features and specific tactical maneuvers.

Table 5. Potential ADAS Feature Impact on Tactical Maneuvers

Man*	ACC	FCW	AEB	RAB	RCTB	ESC	LDW	LKA	LCA	BSM
VP	–	–	–	0	0	+	–	–	–	–
BI	–	–	–	0	0	0	0	0	0	–
PIT	–	–	–	0	0	–	–	–	–	–
MR	0	0	0	0	0	0	0	0	0	0
TB	0	0	0	–	–	0	0	0	0	0
ES	0	0	0	0	0	+	–	–	–	–
RM	–	–	–	0	0	0	0	0	0	0
CH	–	–	–	0	0	0	0	0	0	0
EE	–	0	0	0	0	0	0	0	0	0
PD	–	0	0	0	0	0	0	0	0	0

Note: BI = boxing-in, CH = channelization, EE = emergency escort, ES = evasive steering, Man* = maneuver, MR = moving roadblock, PD = protective details, PIT = precision immobilization technique, TB = tactical backing, VP = vehicle pursuit. "–" indicates a potential negative impact; "+" indicates a potential positive impact; "0" indicates no potential impact.

3.5.2.1 Adaptive Cruise Control (ACC)

ACC provides longitudinal control of a vehicle based on a pre-set speed and the following distance with the leading vehicle. ACC use may lead to over-reliance, and less active LE driver engagement [24], [63]. ACC may interfere with pursuits, ramming, boxing-in, PITs, and channelization, emergency escorts, and protective details if active because the LE driver may need to get closer to the vehicle it is pursuing than the lowest ACC time gap setting available.

3.5.2.2 Forward Collision Warning (FCW)

FCW provides an alert to a perceived imminent collision. FCW would likely be initiated immediately before activation of AEB if an LE vehicle equipped with a collision avoidance system detects closing proximity to another vehicle [29]. While FCW does not actively interfere with vehicle dynamics, FCW alerts during periods of high-stress increase the risk of cognitive overload and distraction [60], [81]. FCW may negatively influence performance during pursuits, ramming, boxing-in, PITs, and channelization if active.

3.5.2.3 Automatic Emergency Braking (AEB)

AEB provides automatic braking in response to a perceived imminent collision. AEB would likely be initiated if an LE vehicle equipped with a collision avoidance system detects closing proximity to another vehicle [31]. This introduces the risk of collisions, and LE losing tactical position while in pursuit. AEB may interfere with pursuits, ramming, boxing-in, PITs, and channelization if active.

3.5.2.4 Rear Automatic Braking (RAB)

RAB is initiated if rear sensors detect an object directly behind the vehicle while backing up [98]. RAB is designed to function at low speeds (1 to 7 MPH), and may malfunction during aggressive tactical backing if active [22], [62].

3.5.2.5 Rear Cross-Traffic Braking (RCTB)

RCTB is initiated if rear sensors detect an object moving behind the vehicle while backing up [36]. Similar to RAB, RCTB is designed to function at low speeds (1 to 7 MPH), and may malfunction during aggressive tactical backing if active [22], [62].

3.5.2.6 Electronic Stability Control (ESC)

ESC stabilizes vehicles dynamics by correcting steering errors by reducing vehicle rotation during periods of unstable driving [38]. Previous work has demonstrated ESC equipped on LE and/or target vehicles influences PIT dynamics, making the maneuver less predictable and riskier [19], [20]. ESC would likely interfere with a PIT maneuver, but may improve driving performance during evasive steering and pursuits by improving stability if active[37].

3.5.2.7 Lane Departure Warning (LDW)

LDW provides alerts to drivers when the vehicle is about to leave its lane, particularly on straightaways and highways with clear lane markings [39]. LDW may negatively influence performance during evasive steering, pursuits, and PITs if active, although LDW alerts may be less disruptive than active assistance being provided by LKA/LCA.

3.5.2.8 Lane Keeping Assist (LKA)

LKA provides steering support to keep a vehicle within its lane [40]. In instances of evasive steering, LKA may provide counter-steering torque to counteract the maneuver. While LKA is designed to be over-ridden by manual force, a driver’s response may result in over-correction [22], [63]. LKA may interfere with evasive steering, pursuits, and PITs if active because LE drivers may need to purposefully exit the marked travel lane.

3.5.2.9 Lane Centering Assist (LCA)

LCA provides continuous steering support to keep a vehicle centered in its lane [41]. In instances of evasive steering, LCA is designed to be quickly over-ridden by manual input, but may provide counter-steering torque to counteract maneuvers [41], [90]. LCA may interfere with evasive steering, pursuits, and PITs if active because staying in the center of the marked travel lane is not always appropriate when executing these maneuvers.

3.5.2.10 Blind Spot Monitoring (BSM)

BSM provides an alert when another vehicle is detected in its blind spot on the driver’s or passenger’s side. While BSM does not actively interfere with vehicle dynamics, BSM alerts during periods of high-stress increase risk of cognitive overload and distraction [47], [60]. BSM may negatively influence performance during evasive steering, pursuits, boxing-in and PITs if active.

4 Human Factors Considerations: The Critical Differentiator

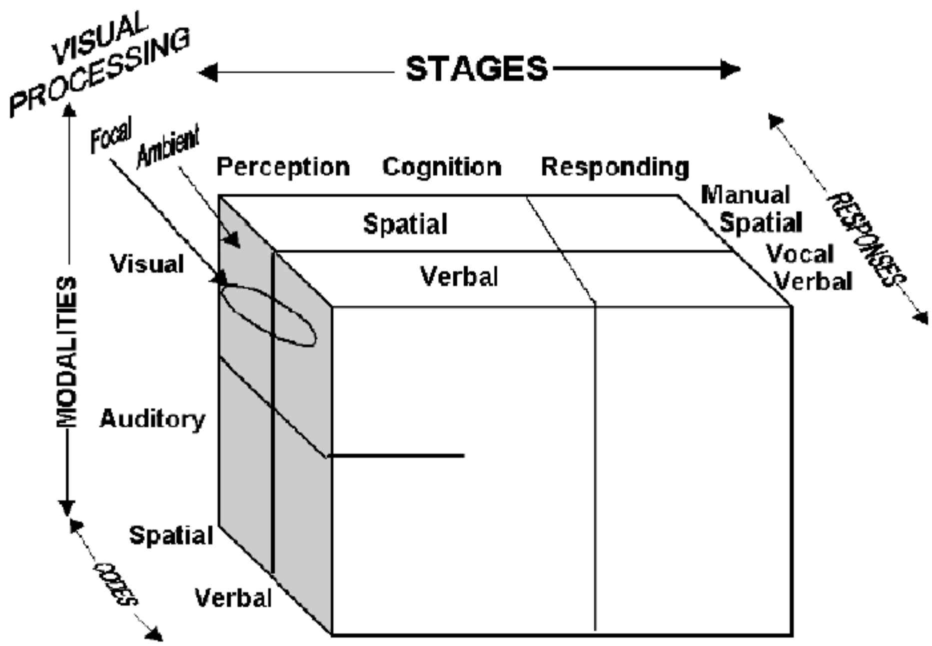
Human factors research broadly covers the body of knowledge that has led to a deep understanding of the human operator's capabilities and limitations both as they impact performance in different environments and as they impact the design of tasks, environments, and systems to optimize performance and safety. Knowledge of human factors issues is central to determining safety outcomes among emergency vehicle operators in two important ways. First, knowledge of human factors issues is integral to the design of driver-vehicle interfaces that aim to proactively maximize performance and safety through the lens of human capabilities and limitations [58]. Researchers and developers of training curriculum can potentially use this information to help first responders identify potential problems with an interface and possible behavioral countermeasures. Second, knowledge of human factors issues is integral to maintaining optimal performance across a variety of operations that vary in time-pressure, stress, and occupational hazards [58]. This information can be useful in designing methods for officers to perform tasks in a manner that maximizes their safety and effectiveness.

4.1 Theoretical Underpinnings of Human-Centered Design

To understand how interfaces and operations can be optimized by the consideration of human factors, it is important to consider fundamental theories of information processing that have informed existing guidelines and recommendations. Two such theories are Wickens' Multiple Resource Theory [81] and Salvucci's Threaded Cognition Theory [82]. It is also important to consider current guidelines for driver interface design in commercial vehicles to understand the fundamental framework of how to maximize driver performance, and the application and translation of those guidelines for first responders [58].

4.1.1 Multiple Resource Theory

Multiple Resource Theory proposes that human attention is influenced largely by different resource pools. Resources essential for attention do not exist in one large undifferentiated pool. Instead, resources are spread across four dimensions: the stages of processing, the codes of processing, the modalities, and the visual channels [81]. The stages of processing dimension posits that there are two different stages, one consisting of perception and cognition, and the other consisting of selecting and responding to information [81]. The codes of processing dimension posits that spatial processing (e.g., sound or light location) utilizes distinct resources relative to verbal processing (words or text) [81]. The modalities dimension is nested within the perception stage and represents the fact that auditory perception uses different resources than visual perception [81]. Finally, a fourth dimension was proposed, visual channels, that is nested within the visual modality. Specifically, Wickens proposed that the focal vision channel is used to process information that is coded either spatially or verbally. For example, reading text (verbal code) requires the focal vision channel, as does identifying finely detailed objects (spatial code). However, the ambient visual channel applies only to information which is coded spatially (e.g., scanning the horizon).



Source: [81]. Reproduced with permission.

Figure 1. Wickens' 4-D Multiple Resource Model.

Wickens' Multiple Resource Theory has been instrumental in the field of human factors. As applied to transportation, this is particularly true in the fields of aviation and driving research [81], [83], [111]. While multitasking while driving may be synonymous with distracted driving in the era of smartphones, multitasking to a certain extent is a natural part of operating a vehicle. Driving often requires an operator to monitor and respond to a number of factors, hence why simulation studies of driving refer to this as a dynamic driving task (DDT). Drivers must monitor their speed and distance, watch for road signs and pedestrians, assess other vehicles' actions for lane changes or turns, and check navigation displays. Based on Wickens' Multiple Resource Theory and its underlying idea of modality-specific cognitive interference during multitasking (e.g., two visual pieces of information that need to be processed centrally at the same time), practitioners are able to model mental workload and driver difficulty based on situational driving conditions [81], [83], [111].

Multiple Resource Theory was applied to driving by Horrey & Wickens [111] to quantify demand and cognitive interference while performing specific combinations of in-vehicle tasks and driving tasks which relied on information outside the vehicle [111]. For example, researchers proposed that city driving and rural curved driving are inherently more demanding than rural straight driving. Similarly, an in-vehicle task with a heads-up display is inherently less demanding than an in-vehicle task with a heads-down center-console display because the driver does not need to glance both outside and inside the vehicle to perform the in-vehicle task with a heads-up display. Total interference is calculated as the sum of the total demand score and resource conflict score [111]. For instance, perceiving a *focal visual* in-vehicle task while performing an *ambient spatial* driving task carries less interference due to limited resource conflict, relative to responding to two focal or two ambient tasks concurrently [111].

4.1.2 Threaded Cognition Theory

Threaded Cognition Theory proposes that individual tasks are separate "threads" that require specific cognitive resources from distinct resource pools, similar to Wickens' Multiple Resource Theory [81], [82]. Unlike Wickens' Multiple Resource Theory, the Threaded Cognition Theory proposes there is no "master controller" or "central executive" organizing and executing tasks. Instead, individual tasks or threads act autonomously, recruiting resources greedily when needed and available, and releasing resources politely when the needs are fulfilled [82]. Task prioritization occurs dynamically through a concept of urgency, in which the task with the longest time not being addressed is prioritized but changes based on the goals of the tasks and resources received [82]. According to Threaded Cognition Theory, multitasking can be productive and efficient if the tasks require dissimilar resources and the threads do not overlap. Cognitive bottlenecks occur when two or more threads attempt to access the same resource across pools of perceptual (visual and auditory), motor, memory, or procedural resources [82].

Threaded Cognition Theory has been integral to driving research by improving researchers' ability to mathematically model precise driver behavior and performance. Specifically, researchers have found that greater working memory load while driving may led to greater lateral lane deviation (poorer lane control) and longer reaction times during braking events (poorer braking ability) [82]. Further, researchers built on this work by demonstrating that individuals with lower working memory capacity exhibited greater lateral lane deviations and longer reaction times during braking events during dual-task driving relative to individuals with greater working memory capacity [112], [113].

This research was instrumental in better accounting for cognitive distraction and subsequent elevated crash risk experienced by drivers while talking on the phone hands-free [114][6]. From a

Multiple Resource Theory perspective, one would predict that a hands-free phone conversation while driving may carry limited interference because the driving task is a visual-spatial-manual task, while a hands-free phone conversation is an auditory-verbal-vocal task [81]. From a Threaded Cognition Theory perspective, one would predict that driving task and hands-free phone conversation both require procedural resources, resulting in a bottleneck [114]. Due to this bottleneck, the driving task and hands-free phone call tasks are not truly being done concurrently. Instead, the operator is constantly switching their attention back and forth between tasks, incurring a switching cost to both tasks [114]. While the cost for the hands-free phone call is likely inconsequential, the cost for the driving task has real world implications. This switching cost for driving leads to performance decrements in response time, meaning that a driver talking on the phone hands-free is more likely to fail to respond to a leading vehicle unexpectedly braking, miss a stop sign on a curvy road, or fail to respond to a pedestrian crossing the road [114].

4.2 Human Factors implications for Driver-Vehicle Interface Design

Wickens' Multiple Resource Theory [81] and Salvucci's Threaded Cognition Theory [82] have both been instrumental in the field of human factors, particularly for the design of driver interfaces in vehicles. Specifically, Multiple Resource Theory has been instrumental in the design of systems to avoid cognitive bottlenecks and interference [81], [83], [111]. Threaded Cognition Theory has been instrumental in the evaluation of design, supporting precise evaluation of systems and distraction simulations [82]. Specifically, Threaded Cognition Theory has been utilized to mathematically model individual tasks as separate autonomous threads during multitasking and is implemented in the broader framework of a cognitive architecture [116]. For example, Kujala and Salvucci [116] utilized this computational model to predict glance behavior and visual distraction across different visual layouts for in-vehicle touch screen displays. The model accurately predicted that a list layout design would meet NHTSA's safety guidelines on glances away from the forward roadway (15% of glances not exceeding 2 seconds), and that none of the layouts would have met guidelines for total glance time (no more than 12 seconds) [116], [117], [118].

Both theories are integral to current guidelines and recommendations around driver-vehicle interface (DVI) designs, such as those published by NHTSA in 2016 [58]. In this report, NHTSA highlights two primary factors to consider in designing driver-vehicle interfaces, driver workload

[6] Note that the evidence for an increase in crash risk during hands free conversations either on a cell phone or an integrated hands-free phone is mixed, some studies showing no increase in crash risk [115].

and distraction [58]. Driver workload and distraction are considered through the lens of Multiple Resource Theory, in which the primary driving task and distractions or secondary tasks, compete for modality-specific resources. Secondary tasks are predicted to degrade driving performance based on the degree of similarity between processing dimensions of the driving task and secondary tasks, in which tasks that require the same perceptual and cognitive resources cause greater performance decrements relative to tasks that require dissimilar resources.

Secondary tasks are also predicted to degrade driving performance based on the time in which the secondary tasks take visual focus away from the road. Specifically, secondary tasks that require longer glances away from the forward roadway are more dangerous than secondary tasks that allow for shorter glances [58]. For example, short glances towards a navigation system to periodically check route maintenance is inherently less dangerous than reading text messages that require extended glance times off the road. This difference in risk is due to the relative difference in eyes-on-road time, lateral control, speed variability, and cognitive workload [84]. This is why NHTSA guidelines for in-vehicle, as well as portable and aftermarket devices, propose that the duration of a single glance away from the forward roadway should be 2 seconds or less, while the cumulative durations of all glances for a secondary task should be no more than 12 seconds from beginning to end [117], [118]. NHTSA also recommends that DVIs be self-paced and interruptible, allowing drivers to pause and resume secondary tasks flexibly so that during critical moments the drivers can focus on the driving task [58].

In addition to interface design having a central role to play in driver workload and distraction, interface design and alert presentation are integral factors in ensuring that operators of vehicles build trust and knowledge in ADAS features [58], [119]. If alerts occur too frequently or are presented in ways the operator finds subjectively annoying, then the operator is likely to lose trust in the ADAS altogether. This may lead to the operator ignoring ADAS warnings when they occur, or disabling ADAS technologies inappropriately [61]. The ideal ADAS-equipped first responder vehicle would support operators in performing their duties more effectively and safely, and would allow for quick and easy deactivation of the ADAS features when situationally appropriate.

4.2.1 The Importance of Multimodal Alerts

Another critical recommendation for DVI is to advocate for multimodal warning systems that utilize two or more of visual, auditory and haptic alerts in response to perceived hazards [58]. Multimodal warning systems support drivers through both minimizing cognitive bottlenecks and utilizing redundancy of alerts across senses as a fail-safe if a singular visual or auditory cue is missed [58], [120]. For instance, a frontal collision avoidance system that only includes a visual warning on the front dashboard may be ineffective if the driver is visually distracted (ex. texting while driving or using an MCT). If the collision avoidance system only includes an auditory warning without any visual alerts (where the latter identify the reason for the alert), then the driver may fail to associate the alert with a forward collision warning. If the frontal collision avoidance system instead utilizes both auditory and visual cues, the driver is more likely to attend to the alert, using visual cues to bypass a auditory specific bottleneck if the driver is performing a task which draws on auditory resources or using auditory cues to bypass a visual specific bottleneck if the driver is performing a task which draws on visual resources [83]. This example assumes that the driver is not performing a secondary task which draws on both visual and auditory resources.

Further, researchers propose that the appropriateness of whether an alert should be delivered across visual, auditory, and/or haptic modalities is dependent on contextual and situational factors, such as the driving environment, urgency of the message, and location of the visual displays [58]. Visual messages are theorized to be most appropriate for presenting complex information that is non-safety critical and does not require immediate action from the driver [58]. Auditory messages are theorized to be most appropriate in communicating high-priority time-sensitive alerts that require immediate attention, such as an imminent collision warning. Haptic messages provide a tactile response and are useful in capturing a driver's immediate attention when auditory messages are likely to be ineffective (i.e., if there is too much background noise, or if the auditory alert is unclear in its associated meaning). In instances of safety critical situations, such as an imminent collision, auditory messages are often augmented with visual or haptic cues to introduce redundancy and clarity [58].

4.2.2 Visual Interfaces

For visual interfaces, researchers propose several important considerations for DVI. First, visual displays should communicate information clearly by utilizing a mix of text, symbols, representations, and graded displays to communicate specific alerts and functions [58]. The location of visual displays is a critical factor in effective message communication. Critical displays, such as those related to safety hazards, should be located within 15 degrees of the central line of sight for an operator looking towards the forward roadway to avoid extended glances away from the forward roadway. Display locations should also be compatible with the intended response, such as visual blind spot monitoring or lane departure warning displays being in areas that demonstrate clear left and right locations, such as side mirrors or the A-pillars [58].

Color should be used as a complimentary feature in alerts and icons, but not the primary method of communication. Color is useful for augmenting the recognizability of icons relying on prior association. For example, red is typically associated with danger, yellow is typically associated with caution, and green is typically associated with normal operations. No more than four colors should be used in these situations, and special consideration should be given to the effects of color contrasts under various lighting conditions [58].

Text should use clear typefaces with recognizable shapes and proper spacing to prevent blurring [58]. Further, the visual angle subtended by text should be at least 20 arcminutes of visual angle; for a display that is 0.5 meters from the viewer, this corresponds to approximately 3 millimeters in height [58]. Display glare is an important consideration for ensuring displays are easy to read. It can be addressed by using dark backgrounds to provide contrast, anti-glare coatings to filter incoming light and reduce reflection, and cowlings to provide shading [58]. Researchers also advocate for greater use of heads-up displays (HUDs) that offer significant advantages in alerting drivers by aligning alerts closely to the forward-facing line of sight of the driver [121]. HUDs hold tremendous benefits for improving braking response times, but should be limited to only safety critical alerts to avoid cluttering the driver's visual field [58]. A more comprehensive explanation of visual interfaces in driver-vehicle design can be found elsewhere [58].

4.2.3 Auditory Interfaces

Auditory interfaces in vehicles are an essential medium to deliver safety-critical alerts to drivers in a timely manner. Auditory interfaces include both simple tones, auditory icons, and speech messages. Through auditory interfaces, a vehicle can communicate urgency, hazard location, and semantic meaning [58], [122]. Different types of auditory displays are more appropriate for specific messages and also vary in their interpretability and response among drivers [58]. Simple tones are flexible and effective in high urgency situations due to their salience but lack clear meaning and can be viewed as annoying [58], [123]. Earcons, abstract sounds with no inherent meaning such as musical tones or beeps, are considered less obtrusive but are only recommended for drawing attention to visual alerts [58]. Auditory icons, environmental sounds that intuitively convey information such as screeching wheels for an imminent collision, are most effective in communicating higher-order contextual information and have been demonstrated to produce quicker reaction times relative to simple tones [58]. However, research suggests auditory icons are also more likely to produce a driver response to a false alarm, and auditory icons are considered the most annoying type of auditory interfaces [58]. Speech messages can be easily understood but may take more time and are more appropriate for less-urgent messages. When used, speech messages should be delivered as concisely and clearly as possible [58].

Urgency is an important characteristic of alerts [58]. Increased urgency can be communicated with irregular harmonic structures, higher frequencies, faster tempos, and abrupt onsets [58]. Messages and alerts should not exceed 90 decibels, but should exceed cabin noise by 10 to 30 decibels [58]. In order to achieve this, vehicles may need to integrate alert systems into existing audio systems in order to pause auditory stimuli during periods of alerts [58]. Auditory warnings should be recognizable and distinct from one another and can be augmented effectively with visual and/or haptic cues. Auditory localization, where a sound is played from a certain direction to cue the driver where to pay attention, may also be an effective aspect of auditory interfaces, but may be less effective than visual localization due to heterogeneity in cabin structure and audio quality [58]. A more comprehensive examination of auditory interfaces for driver-vehicle design can be found elsewhere [58].

4.2.4 Haptic

Haptic Interfaces rely on touch and/or vibration to communicate messages without influencing auditory or visual workload during driving. Researchers distinguish between two types of haptic interfaces, vibrotactile and kinesthetic [58]. Vibrotactile interfaces communicate information through vibrations, typically through a part of the vehicle that is in constant contact with the driver, such as a seat, seatbelt, foot pedals, or the steering wheel [58]. Kinesthetic interfaces communicate information through the influence of limb or body movement, such as when counterforces are applied to the accelerator or braking pedal. Current guidelines propose that vibrotactile displays are generally appropriate for forward collision warning (FCW), with vibrotactile seat and steering wheel vibration also being potentially useful for lateral movement warnings [58]. Kinesthetic interfaces have more diverse applications. Accelerator pedal counterforce may be useful for managing following distance and speed, as well as curve speed and run off the road warnings [58]. For example, in some vehicles increasing vehicle speed beyond the set speed when ACC is active requires extra force on the accelerator pedal. Steering wheel torque may be useful in communicating lateral movement warnings, while seatbelt pre-tensioner and vehicle brake pulses may be most useful for communicating FCW [58]. For example, with LKA, steering wheel torque is applied as the vehicle approaches too close to the edge of the lane in which it is located.

Timing, intensity, location, and distinctiveness are all critical factors in haptic alert delivery. Haptic alerts should be strong enough to adequately alert the drivers and be distinct from common vehicle vibrations felt during driving operations, but moderate enough to not distract the driver [58]. Large vibration areas (such as a driver’s seat) and specific frequency ranges (between 150 and 300 Hz) are recommended for optimal detection. Haptic spatial cueing, applying vibrations to specific components of the vehicle, may also be useful in communicating spatial specific messages [124]. For example, physical resistance or tactile feedback from the steering wheel can prompt drivers to steer in a specific direction during the communication of a LDW [117]. Haptic alerts should often be combined with auditory and/or visual alerts to ensure clarity of communication and to ensure successful message delivery, relying on cue redundancy

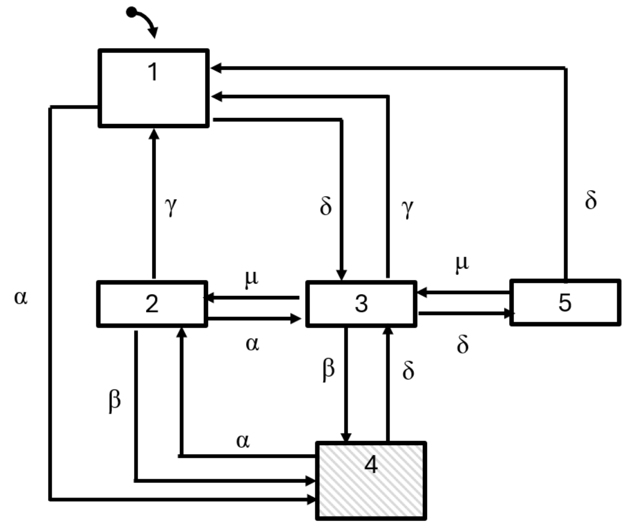
[125]. A more comprehensive explanation of haptic interfaces for driver-vehicle design can be found elsewhere [58].

4.2.5 Formal Interface – Automation Design Methods

Formal methods of assessing the adequacy of an existing automation interface have been developed. Formal methods also exist for designing an adequate interface to automation. All such methods require a way of representing the transition between states in the driver's mental model, states in the interface, and states in the automation. Potential representations include state-transition diagrams [126], order-of processing diagrams [127], and petri nets [128]. Examples are given in seminal works by Degani and Heymann [129], [130]. These methods of representing the adequacy of an interface can be especially important as a training tool when describing interfaces which are and are not adequate to first responders (Section 5).

First, consider a method for assessing the adequacy of a given interface through which an operator controls the automation in order to perform a specific task. Degani and Heymann assume that there are four key determinants of this adequacy: the operator's mental model of the automation's (machine's) behavior; the automation behavior itself; the interface between the operator and the automation; and the specific tasks that the operator wants the automation to perform [129]. They demonstrate that all four components must be aligned to guarantee accurate and reliable interactions between the operator and the automation.

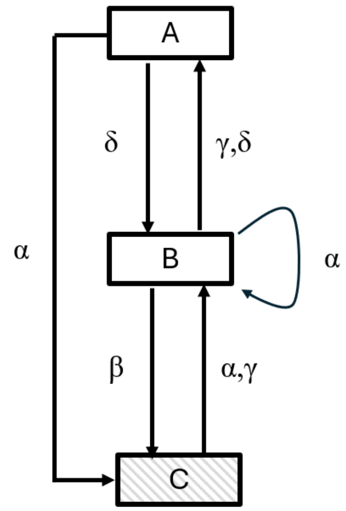
An example from their paper is given below in Figure 2. Suppose that the state transition diagram describes the operation of the automation as it transitions between states. The boxes refer to states and are indexed by numbers. The Greek letters refer to events that trigger the transition between states. State 4 is an illegal state (the gray patterned box) (e.g., the state might be outside the ODD). The operator's task in this case is to control the system so as not to enter State 4.



Source: Based on [129]. Reproduced with permission.

Figure 2. Machine Model

Suppose that the operator's mental model of the machine displayed in Figure 2 includes both the interface components and the operator's understanding of how the automation transitions between states. The operator's mental model is displayed in Figure 3. The operator states are represented by uppercase letters. Note that all of the transition events (Greek letters) are present in the operator's model except μ (i.e., this event cannot be observed by the operator).



Source: Based on [129]. Reproduced with permission.

Figure 3. Operator's Model of the States and Transitions Between States

The question now is whether the operator's model can track the machine state and ensure that it does not enter an illegal state. The automation and operator start, respectively, at State 1 and State A and they move synchronously.[7] Suppose that the operator is in State B and the automation is in State 1. Event α occurs. The automation moves to illegal State 4. However, the operator remains in State B because the mental model is incorrect. But the operator's task was to keep the automation from moving to State 4. So, this composite state (1B, automation State 1, operator State B) is an error state if event α occurs.

With this as background, Degani and Heymann [129] show that a formal process can be used to verify that the user model (which includes the states in the mental model and user interface) and automation model are adequate to the task. Two properties are required. First, for the user model to be adequate the user must be able to determine the state of automation at any given point in time (there can be no error states) and the next state that it will enter for any given event. Second, the user model must be free of blocking states, or states where a user is unaware of certain events that can take place. The formal process is described in detail in Degani and Heymann. The critical takeaway is that a formal process exists for determining whether a mental model, interface, and automation model will perform all tasks flawlessly. In a follow up paper, Heymann and Degani [130] describe a method for automatically generating an interface for the operator that is sufficient for performing the required automation tasks, given that the operator has a correct mental model.

4.3 Driver-Vehicle Interface Design for Law Enforcement

Many of the same important considerations for driver-vehicle interface (DVI) design in consumer vehicles also apply to LE vehicles. DVI for all vehicles must minimize distractions and long glances away from the forward roadway [58], consider limitations in information processing and cognitive architecture in delivering alerts and notifications [81], [83], [111], consider general ergonomics for physical demands, and support driver situational awareness [131]. Yet, there are several important DVI considerations that are unique to LE considering the additional duties of LE, particularly while driving.

LE officers are expected to engage with multi-channel radios, perform tasks on their MCTs, manage siren and light controls, and monitor speed-measuring systems [57]. Importantly, LE vehicles are also often single-crewed rather than double-crewed, meaning LE officers are required to multitask while driving as part of their routine duties [132]. This differs relative to EMS, which is usually double-crewed, and fire trucks which are usually multi-crewed [133]. This allows EMS and firefighters to divide duties, limiting multitasking requirements for drivers relative to LE personnel [133]. Despite a compelling body of research on the effects of distracted

[7] A composite model was constructed by Degani and Heymann [129], but is not presented here.

driving on safety outcomes, most states exempt LE officers from distracted driving laws [134]. One study found that 14% of LE officer involved crashes were attributed to technology distraction, with distractions from MCT accounting for 7% of crashes alone [133], [135]. In absolute terms, LE vehicles are also involved in a disproportionate number of fatal crashes relative to other emergency vehicles, such as fire and medical emergency vehicles [136].

4.3.1 Mobile Computer Terminals

Zahabi and colleagues [121] highlight four key human factors considerations regarding MCTs: officer productivity, physical discomfort, interface usability, and driver distraction. While MCTs enable increased officer productivity by reducing paperwork and real-time database access, they introduce risks related to physical health, cognitive load, and distraction for the LE officer [121]. Researchers have highlighted several issues with using MCTs while driving. Specifically, MCTs are typically mounted near the front passenger seat, requiring officers to glance away from the forward road-way to a greater extent than other common driving distractions [121], [136]. This location also presents risks to officers in terms of physical health. Traditional MCT placement requires an LE officer to rotate their torso and maintain this rotation for a prolonged period of time, potentially resulting in officer discomfort and increased risk of developing musculoskeletal disorders [137], [138]. MCTs also are a concern for distracted driving among LE officers. Previous observational and interview research suggests that LE officers often use their MCTs while driving [85], [139]. In an observational study, Anderson and colleagues [85] observed that 77% of LE officers used their MCT while driving. Further, 55% of officers were observed performing at least one other secondary task while driving, with 7% of officers being observed simultaneously using a secondary object (e.g. radio or cell phone) and engaging with their MCT while driving [85]. Moreover, when LE officers were surveyed regarding 17 recommendations supported by literature reviews aimed at enhancing MCT usability and addressing driver distraction, the implementation of more restrictive departmental policies on MCT use while driving received the lowest approval rating of all recommendations [121]. This suggests little support among regulators and LE officers to prohibit or further restrict MCT use while driving beyond current local and state policies and procedures.

While restriction of MCT use while driving among LE officers appears unlikely, previous research suggests modifications to the MCT interface that can both minimize physical health demands and address distracted driving [121], [136]. MCTs are often mounted center-right to the driver in the direction of the passenger seat, requiring the driver to turn their body and potentially bend during use [137], [138]. Previous work has demonstrated alternative MCT placement can alleviate these concerns, specifically placing the MCT as closely as possible to or in front of the LE officer [121]. While this MCT placement is impractical for officer use while driving, researchers have proposed alternative interface designs to make these recommendations feasible [121]. Zahabi and colleagues [121] propose adaptive information communication and adding a simplified heads-up-display (HUD) to minimize glances away from the forward roadway. Specifically, MCTs can be designed to prioritize the most relevant information to the LE officer in situations of high cognitive load in an uncluttered, simplified HUD display by utilizing machine learning [121]. This may effectively minimize time in which the officer is taking their eyes off the road, reducing crash risk [121]. Alternatively, an officer can engage with a more detailed and traditional display on their MCT console while stationary based on need [121].

4.3.2 Information Presentation

Previous work also suggests that how messages are delivered plays a central role in cognitive workload while driving. Williams and colleagues [93] explored the effects of information presentation on driving performance, gaze behavior, and situational awareness. They manipulated three factors: information availability (auditory + static display, auditory + dynamic display, baseline), communication format (ten-codes, natural language), and event type (dispatch-initiated calls, environmental/patrol-initiated events). Each officer completed a baseline condition plus four combinations of communication format and display type, counterbalanced across participants.

The study found that the ten-codes combined with the auditory + static display condition was the most demanding, resulting in the highest error rate on situation-awareness questions. Situation-awareness accuracy improved with dynamic displays and natural-language communication. Driving performance was not significantly better in the baseline condition compared to the technology conditions, despite more frequent glances to the terminal in the latter [93]. This mirrors similar work by Zahabi and Kaber [136], which found that despite an increase in driver workload, and degradation of visual attention to the roadway and situational awareness, LE officer driving performance while completing a secondary task was not significantly worse than baseline. This studies suggest that LE officers are protective of driving performance while completing a secondary task, and further usability improvements to interface design may address secondary concerns that can increase crash risk such as driver workload, visual attention, and situational awareness [136].

4.3.3 ADAS Interfaces in Law Enforcement Vehicles

Optimal ADAS interface design is essential in optimizing trust and minimizing disuse of ADAS features in LE vehicles. ADAS interfaces should be designed to minimize overall interface complexity, and minimize the number of glances and total glance time away from the forward roadway required to engage with ADAS features [58]. Literature suggests several options for optimizing ADAS design to minimize this risk.

4.3.3.1 ADAS Activation and Deactivation

ADAS activation and deactivation can be achieved through several methods that differ in usability and accessibility. Considering the already cluttered interface of LE vehicles, it may be best to automate ADAS activation and deactivation using vehicle integration systems [17]. Specifically, ADAS activation and deactivation can be integrated with a vehicle's sirens and lights so that ADAS can be selectively deactivated in emergency situations. For example, certain ADAS features that may interfere with a pursuit or evasive driving (such as AEB, LKA, LCA) can be automatically disabled when the sirens and lights are activated, and automatically activated during normal driving scenarios. All three LE vehicles considered in this literature review (2025 Dodge Durango Pursuit, 2025 Chevrolet Tahoe PPV, and 2025 Ford Police Interceptor utility) contain the technological capabilities to enable vehicle system integration [21], [22], [23]. This approach addresses the possibility of human error that may occur with a manual button and allows for LE vehicles to extend their ADAS abilities without further cluttering the DVI.

Automatic ADAS activation/deactivation also minimizes cognitive load and multitasking demands while driving for LE officers. The greatest limitation of this approach is the lack of empirical evidence on which ADAS features would be helpful in emergency situations versus a hindrance [17], [57], [60]. Only one study has assessed the utility of ADAS features (specifically BSM, FCW, and AEB) in normal driving and pursuit scenarios among LE, finding ADAS features were only helpful during normal driving conditions [60]. The findings from this study are largely supported by survey findings on perceptions of ADAS from LE, in which LE officers show an interest in ADAS, but generally prefer ADAS features to be deactivated in pursuit scenarios [17], [57], [62].

Alternatively, manual buttons may be useful to avoid extended time engaging with settings contained within an infotainment system [58]. This includes prioritizing physical buttons for critical functions that may need to be deactivated for tactical driving situations, designing controls to be utilized with only one hand to ensure the other hand remains on the steering wheel, and locating the buttons in an intuitive location where they can be found easily or even without looking [58]. Yet, this may be particularly difficult in LE vehicles considering the already cluttered driver-vehicle interfaces. For LE vehicles, post-market outfitters of vehicles must ensure added equipment (such as MCTs, license plate readers, and speed sensors) do not obstruct the driver's view of ADAS displays or manual buttons [58], [121].

The least advantageous method of ADAS activation/deactivation is utilization of the infotainment system to navigate to system settings. Previous work suggests that it takes much longer to complete tasks using visual-manual interactions with touchscreens than it does to complete the same tasks using auditory-only (verbal commands) or physical-only interactions (knobs or buttons) [140]. Specifically, visual-manual interactions with touch screen increased task to completion time by 104% relative to auditory only interactions, and 89% relative to physical-only interactions [140]. This is particularly concerning considering the emergency scenarios in which LE officers would need to deactivate their ADAS features, during which there is already significant competition for cognitive resources to maintain radio communication and initiate tactical driving [18].

Finally, researchers have proposed that machine learning may be useful in creating adaptive ADAS features that better account for situational context and need in the future [141]. Specifically, researchers demonstrated that random forest and support vector machine algorithms were able to predict whether officers driving in a simulator were engaged in normal or pursuit driving scenarios with 90% accuracy based on driving behavior, simulated vehicle dynamics, eye-tracking, and secondary-task status [141]. These systems could eventually be used to moderate alert presentation and active system reactivity based on the situational needs of the officer [141].

5 Training Considerations and Recommendations

Driver licensing is administered at the State level. While the American Association of Motor Vehicle Administrators recommends that driver educators provide behind-the-wheel instruction on the use of ADAS if equipped, there are no formal licensing or certification requirements required for drivers to use ADAS features; indeed, the guidance recommends that only safety-critical technologies (such as LDW and AEB) be permitted to be enabled during a driver license skills test [142]. Thus, training LE officers on how best to use ADAS will necessarily draw on other sources of subject matter expertise. This section provides recommendations on how LE driving instructors can best prepare both on how to deliver that training – in the classroom, on a test track, in a simulator, or in a vehicle in real time – and on what the content of the training should be in light of what has been discussed above.

Below, the discussion focuses on two areas which may further help inform the method of delivering ADAS training and the content of that training when ADAS is involved. First, LE trainers may benefit from a broader understanding of the most up-to-date research on ADAS training among civilians. Some of these training programs may contain elements that are useful when suitably modified for training LE officers (Section 5.1). Second, because ADAS features vary as a function of a vehicle make, model, year and software update, trainers should consider general training procedures, as well as procedures specific to the implementation of a given feature. Specifically, it is critical that officers be trained on the particularities of the ADAS features as they are implemented in their vehicles. We propose that agentic AI solutions could be useful when applied to the problem created by unique and continually evolving functionalities, operational design domains, and human-machine interfaces are proposed (Section 5.2).

5.1 General ADAS Knowledge and Training Programs

Previous reviews of literature suggest neither the driving public nor first responders understand the capabilities and limitations of ADAS features [143]. Drivers have historically learned ADAS functionalities outside of driver training courses, relying on car dealerships, owner's manuals, vehicle user interfaces, websites [144] and trial-and-error [65]. Below, we consider studies that have examined drivers' general understanding of ADAS features. We also consider studies that explored drivers' more detailed mental models of the relation between the different states of vehicle automation and the information displayed on the human-machine interface. Finally, we describe training programs that address the inadequacies identified.

5.1.1 Drivers' Understanding of ADAS Features

Drivers typically do not understand the ADAS features with which their vehicles are equipped well. For example, in one review of studies of drivers' knowledge of ADAS features [62], drivers often did not know that ACC may not always detect stationary hazards, that LDW and LKA are less effective on roads with poor lane markings, curves, and hills, and that AEB and pedestrian detection systems may not engage properly in poor visibility conditions. Many other studies have confirmed the general public's lack of understanding of basic ADAS features. Perhaps this is not surprising, because the sources they seek information from are not always reliable. One classic study found that in interviews of salespeople at 18 dealerships, the salespeople were not all well informed about ADAS features and, as consequence, sometimes provided inaccurate information on safety-critical ADAS features [145].

Perhaps the most compelling of these studies was one undertaken in Sweden [146]. A field test was used to evaluate drivers' understanding of ADAS features related to braking with ACC. Drivers were reminded throughout the evaluation that they needed to supervise the ADAS features. Moreover, they were informed of system limitations (the ODD). After 30 minutes of driving on a test track (two travel lanes, one in each direction), a lead vehicle pulled into the opposing, empty lane of traffic. When it did such, an object which resembled either a stationary car or large garbage bag was revealed in the driver's lane. Despite the ongoing reminders to supervise the automation and the information provided at the beginning on the limitations of the ADAS ODD, 28% (21/76) of drivers hit the object in front (the car or the garbage bag). Given that the driver's eyes were tracked, one could determine whether the drivers were paying attention at the time of the crash to the object that they were about to strike. All of the drivers who crashed had their eyes on the forward roadway and were glancing at the car or garbage bag.

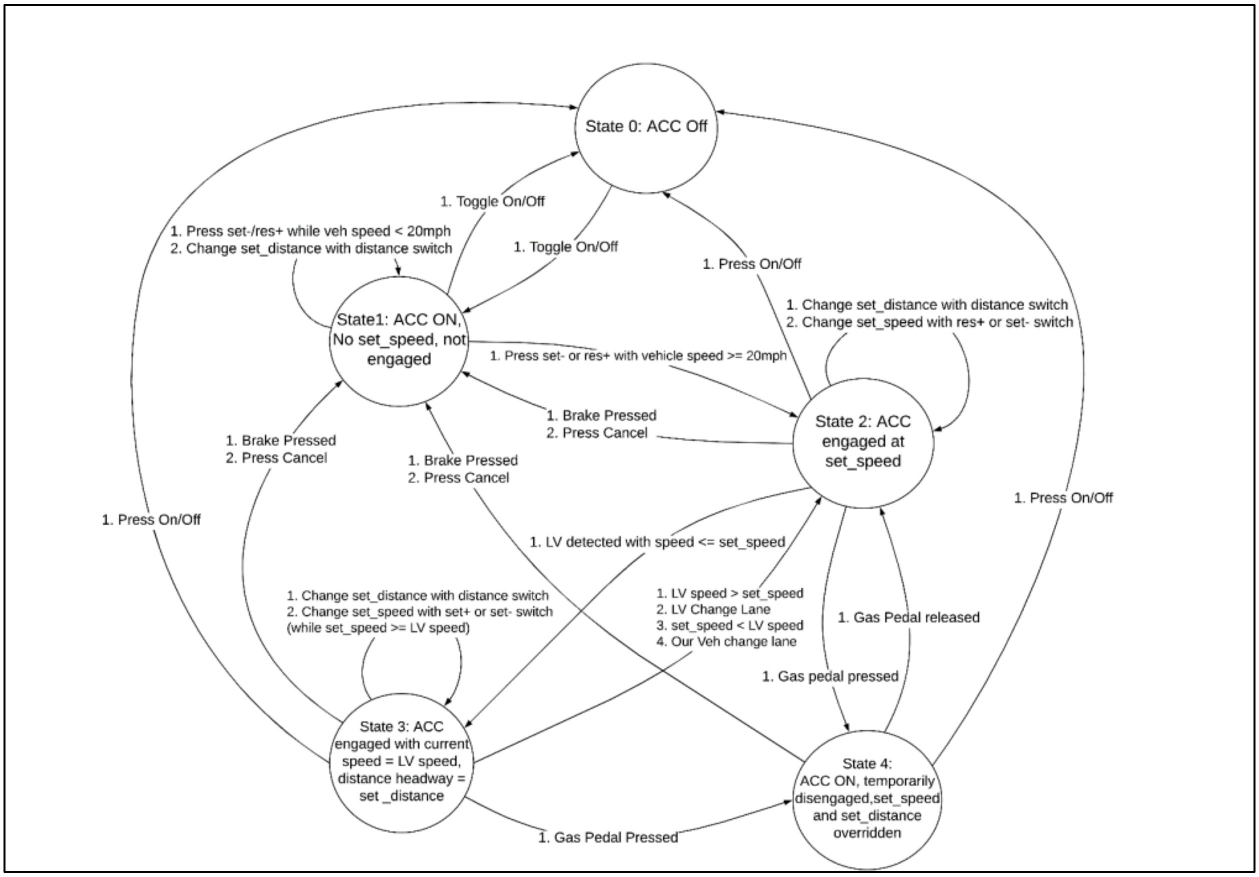
Similar results were obtained in studies by Russell and colleagues [147], [148]. In Russell and colleagues [148], none of the participants intervened when the lead car pulled into the opposing lane and revealed another car traveling in front much more slowly. Participants in this experiment said they wanted to "see what the car would do". In short, even when drivers are told about the limitations of an ADAS feature or features, they may still not operationalize that understanding in ways that help them avoid a crash.

We have also discussed a recent survey of LE officers' understanding of ADAS functionality, of the operational design domain, and of the human-machine interface with which they need to interact [17]. In that survey, only 47% of the respondents answered "Yes" to the question: "Do you know how to easily turn on and off your ADAS features?". This suggests that the HMI is either difficult to operate, or its operation was never fully explained. Again, in the same survey, 62.8% of the respondents answered "Yes" to the question: "Would you use ADAS more if their functionality and advantages were clearly explained to you?". This suggests that advantages of ADAS may not have been explained clearly. Moreover, the fact that between 60 to 81 percent of the crashes that involve LE officers occur during routine driving may be a consequence, in part, of the fact that ADAS features were not activated [11], [12].

5.1.2 Drivers' Mental Models of ADAS

The above studies did not attempt to probe more deeply into drivers' mental models of particular ADAS features. A mental model is useful for identifying and predicting operator errors. Once one delineates a mental model, it is clear that the driver's understanding needs to take into account a number of different factors, both the state of the automation and the ways the automation transitions out of a state. For example, consider a driver's mental model of one version of ACC. The transition diagram in Figure 4 below is a generic model of the states and transitions with ACC [149][8]. The ACC has five unique states (labeled as S0 through S4). A state is defined here by the rules governing its operation. As an example of the transitions that can occur into and out of a state, consider State 1. In State 1, the ACC is turned on and is ready to be used (a transition has occurred from State 0 to State 1), but no speed has been set and it has not yet been used. In order to be set, the speed must be at least 20 mph. A transition is then made to State 2. Note that there are a total of three transitions out of State 1 and four transitions into State 1. One can use this transition diagram along with task analyses to predict possible errors. For example, the driver may assume that the ACC is on (State 1) and can set the speed and following distance, but in fact the driver is in State 0 and so nothing happens. This is an example of mode (state) confusion.

[8] The reader may note how much more complicated a realistic mental model is, as displayed in Figure 4, as opposed to the simplified model presented previously (Figure 3) in Section 4.2.5.



Source: [149]. Reproduced with permission.

Figure 4. Model for Identifying and Predicting Driver Error with ACC

Understanding the driver's mental model can improve training design. Procedures have been described both to assess whether the mental model is correct [129] and, if it is correct, to design an HMI for an operator that allows the operator to perform all automation tasks correctly (i.e., no error states or blocking states) [130].

5.1.3 ADAS Training Programs

There have been a number of programs designed to provide civilian drivers with the training required to better understand ADAS features and, importantly, more safely use ADAS while driving. Several related studies are described below. The studies are important because of the comparison they make between different methods of training. Having said that, none of the ADAS studies that are described assess the driver's mental model. Rather, they assess performance, the hope being that if performance is correct, then so too is the mental model. We comment more on this in our summary statements at the end of this section (5.1.4).

5.1.3.1 Self-Instruction (User Manual), Ride-Along Instruction, and Combination

Perhaps one of the easiest, but most time intensive ways to train ADAS features, is to ride along with an instructor who knows said systems. One of the earliest studies analyzing the criticality of such time intensive training was a study published in 2017 by McDonald and colleagues [89]. Participants were given one of four different types of ADAS instruction: self-instruction (user's manual), ride-along (with instructor), ride along followed by self-instruction, and self-instruction followed by ride-along. Five ADAS technologies were included in the study: ACC, BSM, LKA, parallel parking assist (PPA), and RCTA. The functionality, ODD, and HMI of each ADAS technology were addressed in the training (either in the user's manual or by the instructor in the ride-along). For example, for BSM systems it was stated either in the manual or by the instructor in the ride along that the BSM system will alert the driver when another vehicle is located in the driver's blind spot (function), that the BSM may not detect pedestrians or cyclists (ODD), and that the system may provide an escalated alert if a vehicle in an adjacent lane is in the driver's blind spot and the turn signal is activated (HMI) [89].

In the self-instruction group, an OEM user's manual was modified so that it retained only information relevant to the five ADAS technologies identified in the above paragraphs [89]. Information relevant to the functionality, ODD, and HMI was included in the shorter manual. In the ride-along demonstration, the participant sat in the passenger seat of the vehicle. The instructor explained briefly the location of the sensors that were part of the ADAS features. The instructor then drove a predetermined route, demonstrating the five ADAS technologies as appropriate, discussing the functionality, ODD, and HMI. The drive took approximately 40 minutes.

The evaluation of the training consisted of a pre-training survey and post-training survey of 22 questions. The answer to each question was scored as correct (1) or incorrect (0). There were statistically significant differences in the scores on the pre-training versus post-training surveys for all four groups (10.46 points averaged over all participants out of a maximum of 22), as well as each of the four groups individually. The largest difference was observed with the ride-along plus owner's manual group (17.77 points); the smallest difference was observed with the owner's manual group (15.43 points). The differences between the four groups on the pre-training survey were not statistically significant nor were the differences between the four groups on the post-training surveys statistically significant. This suggests that the ride-along training may need to be changed if its benefits are going fully to be realized.

5.1.3.2 Self-Instruction (User Manual) and Multimedia Instruction

Ride-along instruction is very time intensive. As an alternative to riding along with an instructor, one can potentially gain training benefits by using the in-vehicle HMI without actually driving, providing multimedia instruction to the participant inside a parked vehicle [150]. Towards this end, in a recent study two groups were given an overview of ADAS along with specific training on Traffic Aware Cruise Control and Autosteer as available on a Tesla S. One group read a user's manual to obtain this information (self-instruction group). The second group received instruction inside a parked vehicle (multimedia group). Individuals in both groups were provided with information about the functionality, the operational design domain (where it was appropriate and not appropriate to use), the relevant sensors, and the interaction with the human-machine interface for each ADAS feature [150].

The details of the two instructional methods are as follows. First, the self-instruction group read the portions of the operator's manual about the general ADAS operations as well as the portions specific to Traffic Aware Cruise Control and Autosteer. Second, the multimedia group that interacted with the HMI in a parked vehicle received the same overall ADAS training as well as the specific training on the same two ADAS features. The interface used in multimedia training was designed to resemble the interface used in the actual vehicle. Once a participant in the multimedia group sat in a parked vehicle with the interface, a video instructed the participant to manipulate the controls and more generally interact with the system as he or she would if driving when using the two ADAS features [150].

After training, both groups completed a drive on a test track and then a survey of ADAS knowledge. Participants' eye glance behaviors were evaluated on the test track while performing a secondary task. In the test track drive, no differences were reported in the eye glance behaviors of the two different training groups [150]. In the survey of the participants' knowledge of ADAS, no differences were reported in the knowledge acquired by the two groups regarding the ODD of either Traffic Aware Cruise Control or Autosteer. However, the type of training did have an effect on participants' knowledge of which sensors were active when lane keeping was operational. Those receiving multimedia training were three times more likely to identify the list of active sensors than those who read the manual [150].

5.1.3.3 Self-Instruction (User Manual), e-Learning, and Simulator

If multimedia training in a parked vehicle does not improve learning over self-instruction with an operator's manual, then perhaps a driving simulator would prove more effective because it is more immersive. With this in mind, one study compared the effects of ADAS training in a driving simulator with e-learning and self-instruction (user manual) [151]. The ADAS features that were part of the training included ACC, LKA, automated overtaking[9], and minimum-risk maneuvering. The functionality, ODD, and HMI were included in the training of ADAS features for each of the three groups [151].

[9] The automated overtaking function is initiated by the driver activating the turn signal; once the turn signal is activated, the system evaluates whether a lane change is safe and, if so, executes the lane change and overtaking.

Simulator training was conducted under the supervision of an instructor. Participants engaged in simulated highway driving, during which they were instructed on system operation, including activation, settings adjustment, and appropriate methods for regaining manual control [151]. The experimenter followed a standardized script to ensure consistency and replicability. The participants in the e-learning condition were given a set of PowerPoint slides. Those slides provided the participants with knowledge of the functionality of the ADAS features, the operational design domain, and the interaction with the HMI. Participants in the users' manual condition were allowed a set amount of time to learn about the functionality, ODD, and HMI of the ADAS features of the vehicle [151].

All participants took a practice drive on the simulator before beginning the training. After the training, all participants were given, in order, an online training evaluation survey, three simulator test scenarios, and an online driver skills evaluation. Assessment of participants' performance using ADAS in the test scenarios was undertaken on the driving simulator. The test scenarios included situations requiring the driver quickly to take back manual control of the vehicle. When the ADAS feature was engaged, the driver could regain control by: pressing the brake pedal; pressing the accelerator; or pressing the appropriate LED button on the console. If the driver failed to respond to the takeover request, the system brought the vehicle to a stop. The test scenarios also included situations requiring the driver to re-engage the automation. A fuzzy logic model was used to model a driver's performance [151]. It was a function of (a) the time to activate the system when the driver was prompted to do such; (b) the number of attempts to activate the system when the driver was when prompted to do so; and (c) the time to disengage the system when prompted to take over control.

The model rated 12 of 16 drivers in the simulator training group as very good, 5 in the e-learning group as very good, and 6 in the self-instruction group as very good. Moreover, separate analyses of the participants' performance on the driving simulator in the test scenarios indicated that the time it took drivers to take over control in the simulator training condition was significantly faster than the takeover time in either the e-learning or user manual conditions. This is perhaps the most important, safety critical dependent variable. Unfortunately, no information was given on the actual differences in the takeover times in the three groups, only a report that the differences were significant. Separate analyses also indicated that the simulator-trained group took fewer attempts to activate the ADAS than either the e-learning or user manual participants [151].

To determine whether the fuzzy logic model provided estimates of trainees' performance in the various groups consistent with the subject matter experts' estimates of trainees' performance in the various groups, qualified trainers supervised each drive. They were asked to answer questions for each participant such as: Did the training help participants understand the purpose of the ADAS features (functionality)? Did the training help the participants understand how the features worked (ODD)? Was the participant able to monitor the operation of the features (HMI)? The subject matter experts' estimates were concordant with the estimates of the fuzzy logic model. Specifically, the mean scores on the third test scenario for the fuzzy logic model were 4.88, 4.36, and 4.01, respectively, for the simulator, e-learning, and manual training groups. The mean scores for the subject matter experts were 4.56, 3.54, and 3.31, respectively, for the simulator, e-learning and manual training groups. Note that the maximum score drivers could obtain was 5.0 [151]. The authors concluded that simulator training conducted by the instructor was the most effective training method because it enabled comprehensive familiarization with the material and the opportunity to practice with a knowledgeable instructor [151]. Unfortunately, the descriptive statistics that were used as inputs to the fuzzy logic model were not reported. Thus, it is difficult to know whether the results which are statistically significant are also practically significant.

5.1.3.4 No Training, Video Training, and Simulator Training

A more recent study compared groups given no training, video training, and simulator training on takeover time in scenarios where warnings were issued and takeover accuracy in scenarios where the driver could decide or not decide to take over control [152]. There were two driving modes: manual driving and conditionally automated driving (CAD). CAD is another name for SAE Level 3 driving. Specifically, both lateral and longitudinal location at each point in time were under the control of the automation and, importantly, the driver did not have to actively supervise the automation.

In the control group, participants did not receive any training. The video group and the simulator group were each given three training sessions. In the simulator group, the training was interactive, feedback was available, there were 2 displays, and the length of the training was 150 minutes. In the video group, the training was not interactive, there was no feedback, there was 1 display, and the length of the training was 45 minutes [152]. The detailed qualitative differences between the CAD training in the simulator and video groups are given below in Table 6.

Table 6. Simulator and Video Training [152]

Simulator	Video
Practice how to activate CAD features (disengage from the controlling tasks)	Watch how to activate CAD features (disengage from the controlling tasks)
Practice how to deactivate CAD features (engage to the controlling tasks)	Watch how to deactivate CAD features (engage to the controlling tasks)
Watch what the abilities of CAD are	Watch what the abilities of CAD are
Watch what the limitations of CAD are	Watch what the limitations of CAD are
What are TORs, and how to deal with these requests? Practice them in 3 scenarios	What are TORs, and how to deal with these requests? Watch them in 3 scenarios
When is it necessary to take over the control? Practice them in 3 scenarios	When is it necessary to take over the control? Watch them in 3 scenarios
When is it not necessary to take over the control? Practice them in 3 scenarios	When is it not necessary to take over the control? Watch them in 3 scenarios

Note: CAD = conditionally automated driving, TOR = takeover request

The actual evaluation was done on a driving simulator. There was both a pre-training evaluation and a post-training evaluation. Two general types of scenarios were used. Takeover Required Scenarios (TRS) were instances that were prompted by the automation. Takeover Decision Scenarios (TDS) were instances where the driver had to decide whether it was necessary to take over control [152]. There were 3 TRS scenarios and 6 TDS scenarios. Among the 6 TDS scenarios, it was necessary to take over control in 3 scenarios and not necessary to take over control in the remaining 3 scenarios. In an example TRS scenarios, the driver comes upon a very sharp curve on a rural road. The automation determines that a sharp curve is ahead and requests that the driver take over control, i.e., a Take Over Request (TOR) is issued. In an example TDS scenario where the driver did not need to take over control, the driver navigates a (not very sharp) curve on a rural road [152]. The car slows to 30 km/h before entering the curve. In a TDS scenario where the driver did need to take over control, the driver passed a traffic sign that is broken and cannot be read by the automation but can be read by the driver. The sign indicates that the speed should be reduced from 80 km/h to 50 km/h.

In the TRS scenarios, the Take Over Time (TOT) in both the simulator training and video training groups was shorter on the post-training drive than was the TOT in the control group in the post-training drive [152]. There was no difference in the TOT between the simulator and video training groups in the post-training drives. Importantly, given the link between the standard deviation of lane position (SDLP) and crash risk [153], the SDLP of the simulator training group was less than the SDLP of the video training group and of the control group. In the TDS scenarios, the drivers more often made the correct decisions in the simulator training group (76%) than the video training (63%) and the control group (56%). Importantly, the difference between the drivers trained in the simulator and the drivers trained with the video was statistically significant [152]. Moreover, when comparing the pre-training test drive to the post-training test drive, there was a significant increase in the percentage of correct decisions in the simulator training group and video training group in four of the six scenarios. Looking at just the TDS scenarios where the driver had to take over, the improvement in the simulator trained group on the post-training drive compared with the pre-training drive (16.13 percentage points) was 45% larger than the same improvement in the video trained group (11.13 percentage points) [152].

5.1.3.5 Video (parked) and Video (driving)

Finally, a study by Greatbatch and colleagues [154] divided drivers into two groups. Both groups drove a vehicle with partial automation along a preset, 107-mile route. One group could use a video explaining the ADAS features in a vehicle while it was parked. The other group was invited to listen to short interactive audio/visual messages that explained the ADAS features at preset locations along the route that were deemed to be safe. Both groups also had access to a flip book in the passenger seat that explained the two ADAS features central to partial automation: LCA and ACC. The question addressed in this study was how frequently drivers would engage with the three training materials: the video in the parked car (Group 1), the real time, interactive training messages (Group 2), and the flip book (Groups 1 and 2). This is a critical question for the driving public because multiple studies show that drivers learn largely by trial and error while driving the vehicle [155], [156].

The training was specific to the vehicle and ADAS feature being used by the participants, Ford's Co-Pilot360. In the video and interactive versions of the training, a total of three minutes of content was delivered. In the video training, the vehicle had to be parked. The video was displayed on a tablet in the research vehicle. In the interactive version, the training was delivered on a tablet to the right of the infotainment screen. The messages displayed on the tablet were configured so that they did not require long glances away from the forward roadway. At specific locations which were deemed safe, the drivers were asked whether they would like to learn more about a particular ADAS feature. They pressed a large button on the touch screen indicating that, yes, they would like to learn more or, no, that now was not a good time. If they pressed yes, the first auditory/visual message would play followed by the topic of the next message. Drivers could then again hit the touch screen to play the next message or delay the message. In total, the interactive training consisted of a series of six short audio clips and images, ranging from 15 to about 60 seconds. The functionality, ODD, and interaction with the HMI for each of LCA and ACC were explained for each of the three training groups [154].

The evaluation of the participants' performance included: a) the entire time the participant was in the vehicle (either stopped or moving); b) the post-drive survey; and c) the interview. Four cameras installed in the vehicle provided four different views of the interior and exterior of the vehicle, views that could be used to determine whether the driver was engaged with the video, the interactive training, or the flip book. In the post-drive survey, the participants answered a series of questions designed to assess, among other things, how useful they felt that training actually was [154].

Several important findings emerged from the study. First, participants were significantly more likely to report using the interactive training than the video or flip book. Specifically, self-reported usage was highest among the interactive training group (87.1%), next highest among the video group (63.3%), and smallest for the flip book[10] (55.7%) [154]. Second, more than 80% of the drivers who were given access to interactive training completed all or most of it. About 74% of participants completed all of the interactive training messages (all six messages). Moreover, the participants appeared to pay attention to the training while it was being delivered. Specifically, 74% of the participants paid full attention to the interactive training messages, 24% did not appear to pay attention to any messages, and 2% (1 person) appeared attentive to some but not all messages. The information on completion and engagement was determined by data coders who reviewed the in-vehicle video of the drivers while they were interacting with the training messages. Third, in the post-drive interview, participants were asked if they would use any one or more of the training materials if those materials were available in a new car (e.g., a rental car). In the interactive training group, 74% of the participants said that they would use the interactive training materials. In the video group, 67% said that they would use video. And in both groups, 66% said that they would use the flip book [154].

5.1.4 Conclusions

Three conclusions follow from the studies discussed above. First, a driver's understanding of an ADAS feature (the mental model, Figure 4) must correctly represent how an ADAS feature transitions between automation states [149]. Moreover, the HMI needs to provide the driver with the information that allows the driver to recognize when a transition between states occurs [129], [130]. Only then can the driver be said to understand fully the functionality, the ODD, and the HMI of a given ADAS feature.

Second, among training methods, the more interactive a training method is, the more likely it is to improve a driver's performance in safety critical scenarios. The research by Harari and colleagues [152] makes this abundantly clear. Simulator training was compared with e-training. When prompted to take over control from partial driving automation, participants trained in a driving simulator had a smaller crash risk than drivers given e-training as evidenced by a smaller standard deviation of lane position. Moreover, and perhaps more importantly, when the driver

[10] Recall that all participants had access to the flip book.

was not prompted to take over control, but needed to take over control, the improvement in the simulator trained group was 45% larger than the video trained group. Consistent with the need for interactions with the automation while the vehicle is in motion, ride-along training did not improve ADAS knowledge compared to self-training with a user's manual [89]. The participants in this case sat in the passenger seat and did not interact with the automation. Similarly, there was no difference the effect of self-instruction and a training using a video in a parked vehicle [157]. However, in the two driving simulator studies where the participant did interact with the automation, performance was improved compared with non-interactive training [151], [152].

Third, given the complexity of what must be learned, the highly interactive nature of the learning that is required, and the specificity of what must be learned, there is a need both for more affordable ways of delivering interactive training and for efficiently providing information on the ADAS feature functionality, ODD, and HMI that is specific to the particular feature. As for affordability, virtual reality (VR) driving simulator headsets are several orders of magnitude less expensive than the fixed-base driving simulators that were reviewed in the above studies. Moreover, drivers behave in the VR headset simulators in ways similar to fixed-based simulators [158] and the open road, at least in most scenarios. Moreover, VR headset simulators already have a large base of evidence supporting their use for training in driving [159]. As for the development of generalizable training programs, in the section immediately below we speak to the use of agentic AI to make such development more efficient.

5.2 Development of Agentic AI ADAS Training Program

Almost every driving automation system has a different HMI with which an LE officer would need to interact, a slightly different functionality, and, to make things still more complicated, a different ODD which places limits on the ADAS feature. This makes the development of training programs that generalize across manufacturer's HMIs and ODDs difficult, if not impossible, to create. However, the introduction of agentic artificial intelligence (AI) could change this dramatically. This section aims to demonstrate how agentic AI can address this critical need. Specifically, we believe that an Agentic AI ADAS feature training program could prove useful to the law enforcement driving trainers. Curriculum developers could tailor their training to the set of ADAS features relevant to a given audience.

We describe below the general steps that a training program would need to take to develop an agentic AI ADAS feature training program. To make the steps concrete, we provide a specific example using ACC in a Cadillac CT-6 to illustrate the potential [160]. The steps could be implemented with an agentic AI tool that allows the training developer to control the workflow, introducing various AI models where necessary. Dify is one possible agentic AI tool [161].

We outline seven steps in the proposed development of an agentic AI-based ADAS training program. We indicate the information that a curriculum developer would have to upload in order to provide the training program with appropriate context for its particular needs. ***This information is italicized, bolded, and in green.*** In addition, the information that would be displayed in the training program to the user is provided. It is assumed that each trainer would want to modify the information as appropriate. Where we are simply providing an illustrative example of what is available, **that information is bolded and in red**. While this approach would certainly not replace subject-matter expertise and hands-on instruction, we believe it has the potential to reduce burden on trainers, particularly if they must train LE on a variety of vehicles.

5.2.1 Ingest Users' Manual, Software Updates, and ADAS Training Materials

First, the original ADAS users' manual provided by a manufacturer of the ADAS equipment along with any software updates to the ADAS feature and the original training materials (assuming there are some) need to be uploaded to a large language model. NotebookLM [162] is one such choice (though not the only choice). It is currently free for anyone with a Google account, allowing up to 100 notebooks each with 50 sources each. ***The trainer would simply upload the users' manual through the web portal.***

5.2.2 Identify ADAS Feature Functionality

Second, the trainer needs to identify one at a time the various ADAS features which the agency would like to train. ***The trainer would need to include these ADAS features and upload these ADAS features to the web portal*** (e.g., ACC, LCA is all that would be needed here as input). Once the Center has identified the features, the training program would automatically identify the relevant text describing the features and the relevant images associated with the features. Below is an example of a query that we would include in an agentic AI model that would provide the relevant text in the users' manual along with the related images. **This information would be displayed to a user as part of the training program (see Section 5.2.2.2)**. Again, we assume that each trainer will want to modify the information that is provided by AI to the queries.

5.2.2.1 Query

"Please find information on adaptive cruise control. Provide a bulleted explanation of its features. Then, identify any images in the file that indicate how the drivers need to interact with the displays inside the vehicle of the features associated with adaptive cruise control." Note that this query is part of the agentic AI model; it is not required that the trainer make this query. What we are evaluating is whether we can make generalized queries across different manufacturers' instantiations of ADAS features.

5.2.2.2 AI Answer

Adaptive Cruise Control (ACC) Features

Based on the provided owner's manual, the Adaptive Cruise Control (ACC) system includes the following features:

- **Speed and Gap Control:** The system allows the driver to select a specific set speed and a following gap time (or distance) between their vehicle and a vehicle detected directly ahead.
- **Sensor Technology:** ACC utilizes camera and radar sensors to detect vehicles moving in the same direction.
- **Automatic Acceleration and Braking:** The system automatically speeds up the vehicle or applies limited, moderate braking to maintain the selected following gap.
- **Stop and Go Functionality:** ACC can slow the vehicle to a complete stop behind a detected vehicle.
    - If the stop is brief, the vehicle resumes automatically when the vehicle ahead moves.
    - If stopped for more than two seconds, the driver must press the accelerator pedal or RES+ to resume driving.
    - If stopped for more than two minutes, the Electric Parking Brake (EPB) will apply automatically to hold the vehicle.
- **Go Notifier:** If the vehicle ahead drives away and ACC has not resumed, a "vehicle ahead" indicator flashes, and the Safety Alert Seat pulses or beeps to alert the driver.
- **Driver Override:** The driver can override the system by pressing the accelerator pedal. While overridden, automatic braking will not occur, and the ACC indicator will turn blue.
- **Switching Modes:** The driver can switch between ACC and regular cruise control by pressing and holding the cancel button.
- **Interaction with Stability Systems:** ACC will disengage if the Traction Control System (TCS) or StabiliTrak activates or is disabled.

5.2.3 Identify ADAS ODD

Third, once an LE officer understands the functionality of the ADAS feature, it is important to understand the ODD. In particular, it is important to understand where the feature might not work or might not work as intended. Here is the question to and answer from NotebookLM with respect to the ACC feature. **This information would be displayed to the participant in the training program (see Section 5.2.2.2)**. The trainer does not need to make the query.

5.2.3.1 Query

"Continue the consideration of adaptive cruise control. List all of its limitations, places and scenarios where it might not work as intended. Provide a bulleted list and explanations of why it fails in these scenarios."

5.2.3.2 AI Answer

Adaptive Cruise Control (ACC) has limitations and may not work as intended in several scenarios, primarily because it is a driver assistance system and not a substitute for active driving supervision.

The Adaptive Cruise Control Limitations and Scenarios for Failure:

The system is only an aid and requires constant driver attention, as **ACC has limited braking ability** and may not slow the vehicle down enough to prevent a collision with a vehicle ahead, especially if the vehicle ahead slows or stops suddenly, or enters your lane.

- **Failure to Detect or Brake for Certain Objects:** ACC **will not detect or brake for children, pedestrians, animals, or other objects**.
- **Winding or Hilly Roads:** ACC should not be used on **winding and hilly roads** because the system **may not detect a vehicle ahead**. Specifically, ACC may operate differently in sharp curves and might reduce vehicle speed if the curve is too sharp. When entering a curve while following a vehicle, ACC may momentarily lose detection of the vehicle ahead and accelerate up to the set speed.
- **Obscured Sensors/Poor Visibility:** The camera and radar sensors must be clean for ACC to operate properly. ACC performance is limited when **sensors are blocked by snow, ice, or dirt**. Furthermore, ACC should not be used when **visibility is low, such as in fog, rain, or snow conditions**.
- **Slippery Roads:** ACC should not be used on **slippery roads** where rapid changes in tire traction can cause excessive wheel slip. If the Traction Control System (TCS) or electronic stability control system activates due to wheel spin, ACC will automatically disengage. ACC **will not engage if the TCS or StabiliTrak electronic stability control system is disabled**.
- **Stationary or Very Slow-Moving Objects:** ACC **may not detect and react to stopped or slow-moving vehicles ahead of you**. For instance, it may not brake for a vehicle it has never detected moving, which can happen in stop-and-go traffic or when a vehicle suddenly appears due to a vehicle ahead changing lanes. This is particularly dangerous as the vehicle **may not stop and could cause a crash**.
- **During Acceleration Override:** If the driver uses the accelerator pedal while ACC is active, the ACC indicator turns **blue** to signify that **automatic braking will not occur**. You could crash into a vehicle ahead if your foot is resting on the accelerator pedal during this override.
- **Towing a Trailer:** ACC should **not be used when towing a trailer** as the driver must frequently take over acceleration and braking on steep hills, and ACC will not detect a vehicle in the lane on steep hills.
- **Entrance or Exit Ramps:** Do not use ACC while driving on an **entrance or exit ramp** because the system may not detect a vehicle ahead in your lane, potentially accelerating the vehicle up to the set speed or causing loss of control.

- **Faulty Radar/System Faults:** ACC may disengage if there is a system fault, or if the radar falsely reports blockage when driving in a desert or remote area without other vehicles or roadside objects. A DIC message may temporarily display indicating ACC is unavailable.
- **Vehicle Lane Changes Ahead:** ACC will not detect a vehicle ahead **until it is completely in the lane**. Manual braking may be necessary in this scenario.
- **Temporary Disengagement:** ACC will automatically disengage if the brake pedal is applied, the cancel button is pressed, the transmission is shifted to neutral, or the system is turned off via the On/Off button.

5.2.4 Identify Operation of the HMI

What is very powerful about an LLM such as NotebookLM is that it can link text to graphics in the text so that an explanation of how to operate a particular feature can be explained to an operator by way of an actual visualization. This works for the Cadillac manual because pictures are available [160]. The query below is abbreviated for clarity. The first step involves finding the relevant images. The second step involves finding the particular button associated with a particular operation.

5.2.4.1 Finding Relevant Images

5.2.4.1.1 Query

"*Identify any images in the file that indicate how the driver needs to interact with the displays inside the vehicle of the features associated with adaptive cruise control*."

Note that although hyperlinks are not visible in the text below, they are available in the actual answer. Thus, hovering over the hyperlink on the On/Off button brings up a display (the display is shown in Figure 5. **The information in Section 5.2.4.1.2 would be provided to the trainee**. The trainer does not need to supply any information here.

5.2.4.1.2 AI Answer

Images Associated with Driver Interaction and Displays

The file contains specific images illustrating how the driver interacts with ACC via the vehicle's controls and displays:

- **Steering Wheel Controls:** The image in **Passage** details the buttons on the left side of the steering wheel used to operate the system. These include:
  - **On/Off (J):** Turns the system on or off.
  - **Resume/Accelerate (RES+):** Resumes a set speed or increases vehicle speed.
  - **Set/Coast (SET-):** Sets the speed or decreases vehicle speed.
  - **Cancel (*):** Disengages ACC without erasing the set speed.
  - **Gap Setting ([):** Adjusts the following gap time to Far, Medium, or Near.

- **Instrument Panel Overview:** The image in **Passage** provides a wide view of the dashboard, identifying the location of the cruise control buttons (Item 21) in relation to the rest of the driver's environment.
- **Cluster Icons:**
    - The image in **Passage** shows the cruise control indicator symbol (a speedometer with an arrow), which turns white when ready and green when active.
    - The image in **Passage** shows the gap setting symbol (a vehicle with a wedge indicating distance) used to visualize the following distance setting.

Figure 5. On/Off Button and Other Steering Wheel Controls

5.2.4.2 Finding Relevant Controls

Once the set of controls associated with a given feature, in this case ACC, has been identified, it is necessary to identify which control is associated with which feature of ACC. This is represented by the query and answer below. **The information in Section 5.2.4.2.2 would be supplied to the trainee**. The trainer does not need to supply any input here.

5.2.4.2.1 Query

"Note that there are three images that you displayed, the image on the top left which has 6 buttons, the image on the bottom left that has three buttons, and then the image in the center which has a steering wheel and the controls in the two other images. Would you please say whether the on/off button for ACC is in the top left or bottom left image and, if so, where it is located in the top left or bottom left images."

5.2.4.2.2 AI Answer

Based on the images provided in the file (Figure 5), specifically in the section describing **Adaptive Cruise Control**, the **On/Off button** for the ACC system is located in the **top left image** (the image displaying six buttons).

In that top left image, the On/Off button is located in the **middle row on the right side** of the button cluster. It is the button featuring a **speedometer icon with a small arrow** pointing to the top left of the gauge. It is positioned between the **RES+** (Resume/Accelerate) button above it and the **SET–** (Set/Coast) button below it, and directly to the right of the **Cancel** button (marked with an asterisk/cross).

5.2.5 Develop Pre-test and Post-test

A curriculum developer will want to develop a pre-test and post-test to determine how well the training is working (the material that was given to the trainees as described above and as modified by the trainer). We can use agentic AI here as well. Our experience with many different examples of driver training, including ADAS driver training for the FTA [163], is that a method of training referred to as error training [164] works extremely well, actually preventing crashes [165], [166] and near crashes [167]. That means we need to devise questions on the pre-test and post-test that differentiate between trainees who truly understand what has been presented in the way of functionality, ODD, and HMI and trainees who may have misunderstood what was presented (and choose an incorrect answer, thereby learning through their errors).

With ACC, depending on the particular version that has been implemented, activation can be a two-step process which trainees might not understand regarding the functionality of the ACC. First the ACC needs to be enabled in order either to set a speed or following distance. Then, once it is enabled, the ACC needs to be engaged by first setting the speed and following distance. Trainees might not realize that it needs to be engaged after it has been enabled.

We used NotebookLM to generate five questions that revolved around this potential misunderstanding and choices (answers to the questions) that would reveal whether the trainee truly understood the differences. In the first set of five questions, each of the three answers was correct**. In the second set of questions, the "other" is the correct answer since none of the three choices is correct. The trainee would be presented with only one of the questions on the pre-test and post-test with respect to this particular aspect of the functionality of ACC engagement.** Presumably a trainer would want to alternate questions on the pre-test and post-test targeting functionality, ODD and HMI which had either one correct answer or no correct answer. In none of the above would the trainer need to supply information.

5.2.5.1 Question with One Correct Answer

Below we provide the query that led to the generation of five questions about ACC with regard to its functionality and three answers, one of which is correct.

5.2.5.1.1 Query

"You identified a major point of possible confusion for drivers. Drivers may believe that ACC is engaged when they press the on/off button. They may not know that they also need to press the set button. Ask 5 different questions of a driver with three answers as choices that you think would probe the driver's understanding of whether ACC is just on or, instead, ACC is on and engaged. The three choices should be reasonable ones. Take your time. You really want a question that probes the driver's understanding without giving away the answer."

5.2.5.1.2 AI Answer

Here are five questions designed to probe a driver's understanding of the difference between Adaptive Cruise Control (ACC) being powered "on" versus being fully "engaged" and active.

Question 1: Understanding Dashboard Indicators. You are driving on the highway and press the ACC On/Off button. A **white** cruise control symbol appears on your instrument cluster. What does this white symbol indicate about the system's status?

- **A)** The system is actively controlling your speed and will brake for vehicles ahead.
- **B)** The system is powered on and ready, but you must still press the "SET–" button to engage speed control.
- **C)** The system is in "Standby" mode because the sensors are currently blocked by dirt or debris.

Question 2: Operational Sequence. You have just entered the freeway and want to set your speed at 65 mph. You press the On/Off button on the steering wheel. You then take your foot off the accelerator, but the vehicle immediately begins to slow down. What step was missed?

- **A)** You did not press the "RES+" button to tell the system to look for a vehicle ahead.
- **B)** You did not press the "SET–" button to lock in the speed and activate the system.
- **C)** You did not hold the accelerator steady for at least 10 seconds before releasing it.

Question 3: System Capability in "Ready" Mode. If the ACC system is currently in the "Ready" state (white indicator light) but has not yet been "Set" (green indicator light), how will the vehicle react if traffic ahead comes to a sudden stop?

- **A)** The vehicle will not automatically brake, and you must apply the brakes manually to avoid a collision.
- **B)** The vehicle will automatically brake to a stop, but it will not resume speed afterward.
- **C)** The vehicle will alert you with beeps but will automatically apply partial braking power.

Question 4: Interpreting Color Changes. While driving with Adaptive Cruise Control, you notice the speedometer icon on your dashboard changes from **green** to **white**. What does this change signify regarding your vehicle's control?

- **A)** The system has upgraded from standard cruise control to Adaptive Cruise Control.
- **B)** The system has lost track of the vehicle ahead and is searching for a new target.
- **C)** The system has deactivated speed control and is no longer maintaining your speed or braking.

Question 5: Verifying Activation. Which of the following visual cues confirms that the Adaptive Cruise Control is fully engaged and currently managing your vehicle's speed and following gap?

- **A)** The cruise control symbol on the instrument cluster turns green.
- **B)** The cruise control symbol on the instrument cluster turns white.
- **C)** The gap setting graphic appears on the Head-Up Display (HUD) or dashboard.

5.2.5.2 Question with Other as the Correct Answer

5.2.5.2.1 Query

"Let me reframe the question slightly. You always gave the correct answer as a response. Consider the use of "other" as a response. Give three reasonable responses which are all wrong and then other. Other is the correct response, but you don't specify what it is."

5.2.5.2.2 AI Answer

Based on the sources, here are five questions designed to probe a driver's understanding of the difference between Adaptive Cruise Control (ACC) being powered "on" (Ready) versus being fully "engaged" (Active), with three reasonable but incorrect answers and "Other" as the correct choice.

Question 1: Dashboard Indicator Colors You press the ACC On/Off button on the steering wheel and a **white** cruise control symbol appears on the instrument cluster. What is the current status of the system?

- **A)** The system is engaged and actively is maintaining your current speed.
- **B)** The system is malfunctioning and requires service from a dealer.
- **C)** The system is actively braking to hold the vehicle in place.
- **D)** Other.

Question 2: Controls for Activation You have turned the system on, and the white ACC symbol is displayed. You have reached your desired highway speed. If you take your foot off the accelerator **without** pressing any other buttons, what will the vehicle do?

- **A)** It will automatically maintain your current speed.
- **B)** It will detect the vehicle ahead and automatically match its speed.
- **C)** It will accelerate to the last speed stored in the memory.

- **D)** Other.

Question 3: Disengagement Behavior You are driving with ACC fully engaged (green symbol). You tap the brake pedal to slow down for a moment. What is the new status of the ACC system immediately after you release the brake?

- **A)** It shuts off completely and the icon disappears.
- **B)** It remains engaged (green) and immediately accelerates back to the set speed.
- **C)** It enters "Override" mode, indicated by a blue symbol.
- **D)** Other.

Question 4: System Capability in "Ready" Mode If the ACC system is currently in the "Ready" state (white icon) but has not been set (not green), how will the system respond if you rapidly approach a stopped vehicle in your lane?

- **A)** It will automatically apply the brakes to bring the vehicle to a stop.
- **B)** It will automatically steer the vehicle into the adjacent lane to avoid a crash.
- **C)** It will limit your vehicle's speed to 25 mph (40 km/h).
- **D)** Other.

Question 5: Activating from a Cold Start You have just started your car and entered the highway. You want to use Adaptive Cruise Control. Which button sequence will successfully engage the system and set your current speed?

- **A)** Press the **RES+** button only.
- **B)** Press the **SET–** button only.
- **C)** Press and hold the **Cancel** button.
- **D)** Other.

5.2.6 Consistency Check

Before providing trainers with the material that they may decide to use for providing information to first responders on the functionality, ODD, and HMI of particular ADAS features, it is important to determine that nothing was missed. At this point, the workflow would add an AI model that would be given the information provided by the first model and be asked to determine whether anything was missing and whether there were any inconsistencies across the description of the functionality, ODD, and HMI of a particular ADAS feature. A similar check needs to be made of the questions that will be asked on the pre-test and post-test of the trainees.

5.2.6.1 Training

Different LLM models can be used to identify the functionality, ODD, and HMI in a given manual associated with each ADAS feature. Before providing the training to trainers, a second LLM should presumably be used to produce the same content as the first LLM. A third LLM can check for consistency between the content produced by the first LLM and the content produced by the second LLM and generate a list of inconsistencies if any exist. This list would be flagged for subject matter experts to inspect.

5.2.6.2 Pre-test and Post-test

The same check would need to be made on the questions and answers to be used on the pre-test and post-test. A second LLM could be used to generate questions and answers using the same prompts. A third LLM could then decide which of the questions are most likely to confuse the trainee and rank them in order. The third LLM would also be asked to determine whether some of the answers are too obviously incorrect and, if so, identify them.

5.2.7 Subject Matter Expertise

Ultimately, the material delivered to the trainees needs to be vetted by the instructors. If that is the case, one might ask what efficiencies are achieved by inserting artificial intelligence into the workflow. The answer is a threefold one. First, users' manuals are very large documents, often running to hundreds of pages. Locating all of the information with respect to the functionality, ODD, and HMI of a particular ADAS feature may not be as simple as searching the table of contents or index and reading the relevant sections. Even scanning the document in electronic form may miss critical material. We believe that trainers who are subject matter experts in both training and the ADAS feature should find that this greatly reduces their burden. Second, the generation of answers to questions that evaluate a user's understanding of a particular aspect surrounding the functionality, ODD, or HMI of an ADAS feature is a very time-consuming task. It remains to be seen whether the AI generated answers really do test the trainees' understanding, so trainers are essential here. Third, subject matter experts who have operated a first responder vehicle with the automation installed may know additional areas where the ODD is limited or the HMI is difficult to operate.

6 Conclusions and Future Directions

Our major conclusions follow, along with additional research needs. In brief, we believe that ADAS can decrease crash risk for LE officers in routine operations. However, that comes with a caveat. There are potential limitations of ADAS features in tactical and emergency maneuvers. However, those limitations can be overcome, in part, by careful design of the human-machine interface and by appropriate training. These conclusions and future research directions are discussed in more detail below.

6.1 ADAS Holds Tremendous Potential in Routine Operations

First responders face a disproportionate risk of injury and death in the service of their communities [10]. ADAS technologies, specifically those focused on collision avoidance, have demonstrated tremendous potential for reducing crash risk in the general population [29]. Considering that 60 to 81 percent of police crashes occur during routine driving conditions, these systems likely hold similar potential, or even greater benefits, to LE officers [11], [12]. The set of activities in which LE officers are asked to engage while driving differs the set of activities in which the motoring public engages in important ways. Specifically, LE officers are often required to use communication systems and/or mobile computer terminals while driving [85]. First responders are also more susceptible to drowsy driving relative to the general population, a susceptibility influenced by occupational hazards, common sleep disorders, and shift work [77]. Considering these additional risks, collision avoidance systems should be used when appropriate in vehicles of first responders.

6.2 The Limitations of ADAS in Tactical and Emergency Driving

While collision avoidance systems are likely effective in mitigating motor vehicle crashes among first responders during routine driving conditions, research suggests these benefits likely do not generalize during pursuit scenarios for LE officers [60]. Pursuit and emergency response scenarios are cognitively demanding. During these high-stress scenarios, alerts such as forward collision warning (FCW) and blind spot monitoring (BSM) may compete for existing cognitive resources, diminishing situational driving performance during critical periods. Alternatively, the alerts may not be salient enough for drivers to process the alerts for their intended safety benefits [60]. Field studies and survey-based research also suggests that physical interference of ADAS during tactical maneuvers and pursuit scenarios is an important concern of LE personnel [17], [19], [20]. As a whole, LE officers are concerned that ADAS equipped vehicles are incapable of taking into account the operational context and situational needs of LE officers [17].

6.3 Maximizing Benefits and Minimizing Pitfalls through Officer-Centered Design

To maximize the safety benefits of collision avoidance systems while simultaneously minimizing the tactical pitfalls, manufacturers and outfitters of LE vehicles must design driver-vehicle interfaces that enable flexible and adaptive ADAS. Officer-centered design starts with creating driver-vehicle interfaces that help LE officers complete their duties safely and efficiently. Considering this, it is very important for driver-vehicle interfaces in LE vehicles to minimize clutter and choose control locations that will not be physically blocked by secondary outfitted devices like an MCT or radar devices [121]. These systems must allow LE officers to utilize ADAS in normal driving conditions, while also enabling officers to quickly and efficiently deactivate ADAS features that may lead to tactical interference based on situational needs. This may include designing specific ADAS features which could be sources of interference (AEB, LKA, LCA, etc.) so that they automatically deactivate when lights and sirens are activated. Additionally, ADAS deactivation using physical buttons that are easily accessible is an appropriate option considering first responders needs.

6.3.1 Simplifying ADAS Deployment: Safety Over Convenience

Emerging research suggests that certain ADAS features offer greater safety benefits relative to others [24], [43]. Specifically, research suggests that certain ADAS features like ACC, and level 2 partial automation systems like ACC + LCA offer little to no safety benefits above ADAS features focused on collision avoidance systems like AEB, LKA, FCW, and BSM [24], [43]. In fact, researchers argue that ADAS features like ACC and partial automation systems are often misused by drivers, introducing new safety risks from over-reliance and poor mechanistic understanding [43]. Researchers recommend that ADAS in LE vehicles should prioritize collision avoidance systems and avoid adding convenience-focused systems that may add clutter and complexity to a driver-vehicle interface that is already complicated by MCTs and other LE-specific equipment [17].

6.3.2 ADAS Training Recommendations

There is currently a large need for ADAS training among LE personnel. Specifically, there is a need for LE to understand ADAS specific to their vehicle for personal safety [62], and a need to understand ADAS features on civilian vehicles to better characterize causal and contributing factors in vehicle crash investigations [63]. Most LE officers currently learn about ADAS through trial and error as they utilize these systems over time [62], [64]. This method of ADAS learning is inefficient and potentially dangerous because users may not fully understand the functionality and ODD of these systems, or how best to interact successfully with the HMI in order to perform a given task. Learning ADAS through trial and error can lead operators to misinterpret sensors, conflate functions, and over-generalize the performance of a system in a specific situation to situations outside of the ODD [65], [89], [154]. Instead, training should utilize a phased education model in which classroom instruction is used to establish accurate mental models of relevant ADAS features, and hands-on experience in a simulator or a test track is used to supplement accurate mental models with the tactile, physical experience of ADAS features when implemented [65]. Research has demonstrated that hands-on training when combined with classroom training is associated with superior operational performance [151], greater knowledge retention of ADAS limitations [65], and optimal trust calibration, relative to classroom training alone [65]. AI agentic models may be particularly useful in the development of vehicle-specific training courses when paired with instructors with subject matter expertise.

6.4 Research Needs and Future Directions

Current research on the potential and limitations of ADAS for first responders is extremely limited. While ADAS, specifically collision avoidance systems, have been demonstrated to reduce crash risk in the general population, no study to date has explored this in first responders [9]. To address the current lack of ADAS-relevant retrospective crash data in first responders, stakeholders should aim to establish reporting mechanisms that enable the creation of a more comprehensive datasets of crashes of LE, EMS, and fire vehicles [16]. While civilian crashes are aggregated through insurance claims and standardized national sampling systems, no such aggregation is done for crashes related to first responders [9], [16]. The Fatality Analysis Reporting System (FARS) is the only currently publicly available database that includes detailed information on crashes involving LE. However, FARS applies a strict inclusion criteria, in which a crash is only included if a fatality occurs within 30 days of the incident [9]. This excludes crashes involving only non-fatal injuries, or significant property damage.

Further, ADAS is not considered in FARS reporting, limiting applicability for this research area [9]. Expanding ADAS consideration in state crash reporting would also be beneficial for understanding the potential safety benefits and limitations of novel ADAS features, potentially aligning with current mandatory reporting regarding level 2 ADAS-equipped vehicle crashes required by NHTSA Standing General Order (SGO) 2021-01 (as amended) [168]. Once adequate data is available, statistical techniques such as quasi-induced exposure [32], [42] and binomial regressions [29] can be applied to understand the influence of ADAS features on relative crash risk. One gap in including broader consideration of ADAS in crash reporting is the currently reported lack of training on ADAS technologies among crash investigators [63]. Increased training and use of ADAS on LE vehicles has the potential to improve LE officers' understanding of ADAS features and how they may contribute to or mitigate a crash they are investigating.

Another major limitation in characterizing the utility of ADAS for first responders is the lack of studies that explore the effects of different ADAS features on driving performance under specific conditions in these cohorts [17], [57], [60]. Only one study (n = 18) to date has explored whether crash avoidance systems improve driving performance and situational awareness under normal and pursuit driving scenarios in LE [60]. As law enforcement officers may drive different vehicles when off duty, with different sets of ADAS features and interfaces, any training procedure must emphasize any differences between systems installed on civilian vehicles and those installed on LE fleets.

Further, only one study to date has assessed whether ADAS is useful for firefighters and EMS personnel [94]. More studies are needed to assess the utility of specific ADAS features for first responders to understand whether safety risk reductions demonstrated in civilian populations transfer to LE officers, firefighters, and EMS personnel under non-emergency driving conditions.

While most LE vehicles are consumer vehicles upfitted and modified for police use, ambulances and fire trucks are dramatically different in weight and vehicular dynamics. This suggests that driving simulator studies similar to Shahini and colleagues [60] and Simeonov and colleagues [94] need to be conducted for firefighters and EMS personnel to better understand the utility of ADAS during routine and emergency scenarios, considering the unique vehicle dynamics of ambulances and fire trucks. Additionally, research on heavy-duty vehicles could be applicable to larger tactical law enforcement vehicles deployed in certain situations.

Further, no studies have been conducted exploring the potential tactical interference of ADAS features, except for ESC while employing a PIT [19], [20], [93]. Based on this, it is difficult to clearly identify and predict how ADAS features would react in specific tactical scenarios beyond what can be surmised from the ODD. To address this limitation, researchers should utilize simulation tools to model how specific ADAS features focused on collision avoidance, such as AEB and LKA, would react under realistic emergency and pursuit scenarios [169]. For example, Virtual Forward Simulation (VFS) tools are able to model high-risk scenarios in which ADAS interference could cause injury or death to LE officers, firefighters, and EMS personnel [169]. VFS tools rely on reduced order dynamic models that allow for the complex wheel engagement and vehicle dynamics necessary to analyze how collision avoidance systems like AEB and LKA may react during tactical and emergency driving [169]. After modeling studies are conducted, simulator or test track studies can be used to validate and extend model findings [19], [20], [93].

At least one commercially available ADAS feature demonstrated worse performance detecting someone wearing high-visibility clothing compared to standard clothing [107]. One direction for future research could be to evaluate ADAS features and develop testing requirements or standards before adopting them for use on LE vehicles to avoid such issues. Training officers on how ADAS features work to detect their surroundings may also help them ensure they are visible to both humans and sensors when they are working in the roadway.

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