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# The Evolution of ADAS Safety: A Human Factors Perspective

**Iiona D. Scully,[1] Abigail G. Swenson,[2] Stephanie M. Reeves,[1] and David M. Cades[3]**

[1]Exponent, Inc., Natick, MA 01760, USA
[2]Exponent, Inc., Warrenville, IL, USA
[3]Exponent, Inc., Chicago, IL, USA

## ABSTRACT

Safety discussions regarding Advanced Driver Assistance Systems (ADAS) have continually evolved as technological capabilities, market penetration, and empirical evidence have advanced. Human factors research on driver assistance technologies has included work on potential unintended consequences, including false alarms, driver annoyance, startle effects, diminished vigilance, behavioral adaptation, and overreliance. As systems have moved from concept to deployment, researchers have evaluated whether such concerns have materialized in real-world use conditions and whether ADAS deliver measurable safety benefits. This paper reviews the evolution of ADAS research using Forward Collision Warning (FCW) systems as a continually evolving example of ADAS features, and examines evidence supporting benefits from Level 1 and Level 2 ADAS. Prior studies have emphasized acceptance, warning design, and trust, as well as potential improvements in hazard perception and response and reductions in rear-end crash rates. Initial concerns that Level 1 and Level 2 ADAS technologies might reduce driver engagement and encourage secondary task use continue to be examined as technology proliferates. Evidence suggests that drivers generally adapt their behavior in response to system capabilities and driving demands, and maintain engagement with the driving task as needed while benefiting from reduced workload. Emerging crash-based evidence also suggests potential safety benefits associated with ADAS, though continued research is needed due to limitations related to data availability, market penetration, and uncertainty regarding system engagement during crashes. Collectively, literature demonstrates how ADAS safety cases have matured over time, evolving from hypothetical concerns and projected benefits to evidence informed by large-scale deployment and real-world performance.

**Keywords:** Advanced driver assistance systems, Human factors, ADAS, Safety, Level 2, FCW, Forward collision warning, Level 1, Level 0

## INTRODUCTION

In the United States, the safety case for Advanced Driver Assistance Systems (ADAS) has continually evolved alongside technological progress and regulatory action. From conception of these systems through implementation and proliferation, human factors research has focused on understanding the impact of human behavior on the ADAS safety case, considering whether these technologies would be accepted, used, or even misused by drivers, and

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whether such behavior slows or moderates the expected and actual ADAS safety benefits.

## METHODS

This paper presents a narrative discussion and review of the evolution of the safety case for Forward Collision Warning (FCW) and comparatively, the safety case for Level 1 and Level 2 ADAS. The literature was selected to illustrate this evolution and include work identifying potential human factors concerns as well as work related to driver behavior and crash risk with these systems. This review is not intended to constitute a systematic or exhaustive review.

## THE EVOLUTION OF THE SAFETY CASE FOR FORWAD COLLISION WARNING

As one of the more widespread Level 0 ADAS systems in the United States, the evolution of research and development of FCW systems provide an example of how the safety case for this system has evolved over time. Prior to the first application of FCW in the United States on select vehicles in 2001 (MY 2001 Mercedes-Benz S-Class Brochure; MY 2001 Mercedes-Benz CL-Class Brochure), early Level 0 ADAS-related human factors work in the 1990s and early 2000s looking at FCW posited that warning drivers just before a collision occurred could reduce the frequency of front-to-rear collisions (NHTSA, 1996; Brown et al., 2001). As manufacturers began working to develop these technologies, the National Highway Traffic Safety Administration (NHTSA) and other researchers examined the potential benefits as well as the potential drawbacks in implementing these systems. In 1995, Tan and Learner showed that driver acceptance was impacted by the sound of the warning and underscored the need to develop effective and non-irritating signals (Tan & Lerner, 1995). In 1996, a NHTSA working group suggested that a front-to-rear collision "driver warning system" was estimated to reduce lead vehicle decelerating accidents by 42% and stationary lead vehicle scenarios by 75% if the system worked perfectly (NHTSA, 1996). Then in 1997, Parasuraman and colleagues considered driver acceptance and trust as it related to the frequency of FCW false alarms concluding that "for the experienced driver … the only acceptable system would be one with a false alarm rate indistinguishable from zero" (Parasuraman et al., 1997). Similarly, in their 2007 NHTSA report, Campbell and colleagues stressed the need to minimize false and nuisance alerts due to potential degradation in driver trust and satisfaction (Campbell et al., 2007). Researchers were also interested in investigation of whether FCW may distract or startle the driver (Campbell et al., 2007), and how that possibly could interfere with the driver's ability to execute an avoidance maneuver if they were already planning or were in the process of responding (Brown et al., 2001). Others were concerned that FCW could lead to drivers to become less vigilant when watching for hazards (Lee et al., 2002). Despite concerns about the potential drawbacks, over time as these systems were implemented, subsequent studies increasingly

documented behavioral and safety benefits. For example, a number of studies from the 2000s and 2010s have suggested that the presence of a FCW may help drivers who are momentarily distracted perceive and respond faster to a hazard as compared to drivers with no FCW system (See Scully et al., 2024 for review). Researchers also posited that FCW may reduce driver workload and encourage safer driving habits (de Winter et al., 2014).

By the mid-2010s, the proliferation of FCW systems on the road allowed researchers to compare crash rates. In 2017, Cicchino demonstrated that FCW led to an approximate reduction of 27% of police-reported front-to-rear crashes when vehicles were equipped with FCW alone, and an approximate reduction of nearly 50% with both FCW and Automatic Emergency Braking (AEB), concluding that almost 1 million police-reported front-to-rear crashes in the United States could have been prevented if all vehicles were equipped with FCW and AEB that performed similarly to the systems in their study (Cicchino, 2017). Recently the Partnership for Analytics Research in Traffic Safety (PARTS), a partnership between automakers and NHTSA, conducted an analysis of FCW and AEB real-world effectiveness and found a 49% reduction in front-to-rear crashes for model year (MY) 2015–2023, a 46% reduction for MY 2015–2017, and a 52% reduction across MY 2021–2023 (PARTS, 2022, 2025). Taken together, despite early pre-proliferation concerns, recent crash data suggests that these systems have an overall safety benefit and that improvements in technology (e.g., reductions in false alarms) and in driver acceptance of and experience with the technology (e.g., through use, reading owner's manuals, education at the point of sale; Hoyos et al., 2018) may underlie these benefits (Cox et al., 2025; PARTS, 2022, 2025).

## THE EVOLUTION OF THE SAFETY CASE FOR LEVEL 1 AND LEVEL 2 ADAS TECHNOLOGIES

Like FCW, the data to support the safety cases for Level 1–2 technologies continue to grow and become refined over time. Level 1 involves sustained longitudinal (e.g., Adaptive Cruise Control (ACC)) or lateral support (e.g., Lane Centering Assistance (LCA)) while Level 2 systems combine the longitudinal and lateral components of Level 1. One of the earlier Level 1 systems (ACC) was first introduced on select MY 2001 vehicles (MY 2001 Mercedes-Benz S-Class Brochure; MY 2001 Mercedes-Benz CL-Class Brochure), while early Level 2 systems were first introduced in select MY 2014 vehicles (MY 2014 Honda MDX Owner's Manual; MY 2014 Honda RLX Owner's Manual; MY 2014 Mercedes-Benz S-Class Owner's Manual). Unlike FCW, which was estimated to be equipped on 94% of vehicles for MY 2023, Level 1–2 technologies have had a slower adoption and growth rate, with approximately 54% and 68% of MY 2023 vehicles estimated to be equipped with LCA or ACC, respectively, and approximately 34% of vehicles estimated to be equipped with a Level 2 feature (PARTS, 2025). Although these are often touted as convenience systems, research on Level 1 and Level 2 ADAS has emphasized both the potential to reduce driver workload and the capacity to reshape driver engagement with the driving environment. Early work demonstrated that ACC and LCA could

lower cognitive and physical demands and enhance situational awareness (de Winter et al., 2014). Research has also suggested that ACC may result in fewer lateral deviations and allow drivers to maintain a larger safety margin (i.e., headway) during mild and moderate braking events (see Aldugom et al., 2025 for review). Similarly, empirical studies show that experienced Level 2 users often develop more dispersed scanning patterns and spend more time monitoring the forward roadway and mirrors than during manual driving, which suggests an adaptation of attentional strategies (Mueller et al., 2021). Longitudinal studies further indicate that Level 2 use could moderate certain risky behaviors, such as reducing speeding among experienced users (Dunn et al., 2019).

With continued proliferation and market penetration of Level 1 and Level 2 technologies, researchers have become increasingly focused on driver engagement, disengagement, and secondary task usage while using these systems. Regarding Level 1, several early studies raised concerns that ACC may result in reduced head movements or decreased attention to the forward roadway (Malta et al., 2012; Morando et al., 2016; Morando, 2017; Rudin-Brown, 2010; Rudin-Brown & Parker, 2004; Tivesten et al., 2015; Lee & Nam, 2003). Despite these findings, later research demonstrated that most glances away from the forward roadway while using ACC were driving related, that drivers were responsive to hazard cues, that drivers kept their attention on the driving task in critical situations, and that drivers showed anticipatory responses in these situations (Morando et al., 2016, 2017; Malta et al., 2012; Tivesten et al., 2015). Findings related to driver engagement in secondary tasks were also mixed, with some research showing lower levels of secondary task engagement when compared to manual driving (Reagan et al., 2021), others finding increased secondary task engagement, but only for experienced ACC users (Naujoks et al., 2016), and others still finding that secondary task engagement decreased with ACC experience (Reagan et al., 2021). Overall, this work suggests that drivers display adaptive behaviors based on the driving environment while using ACC.

Similarly, researchers have become interested in understanding the potential for how reduced manual control through the use of Level 2 driving system might enable mind-wandering or non-driving secondary tasks, particularly as drivers grow more comfortable with the systems (Endsley, 2017; Reagan et al., 2021). Yet, similar to Level 1 technologies alone, findings have been mixed: while some studies documented reductions in forward-roadway glance allocation or increased secondary task use as compared to manual driving (Morando et al., 2020; Reagan et al., 2025), others found no meaningful increase in secondary task engagement or misuse compared to manual driving, especially among experienced users capable of strategically timing secondary tasks (Shutko et al., 2018; Lin et al., 2018; Dunn et al., 2019; Russell et al., 2018). Consistent with this finding, a recent meta-analysis indicated that the increase in secondary task engagement while using Level 2 technology was present in simulator studies, but not in on-road experiments, with the authors noting that the evidence on secondary task engagement should be considered preliminary (Vasta & Biondi, 2025), providing further support for the idea that drivers using these technologies display adaptive behaviors consistent with the varying demands and complexities of the driving task.

As Level 2 technology has continued to develop and become available to consumers, recent research has examined how drivers actually use Level 2 systems in everyday contexts. Across large-sample surveys and policy-oriented reviews, drivers report that Level 2 driver assistance meaningfully reduces cognitive load by taking over routine longitudinal and lateral control, allowing them to reallocate attention more efficiently to the roadway rather than disengaging from it (Carsten et al., 2023; Mueller et al., 2022). Survey evidence also indicates that while users may occasionally engage in secondary tasks, most drivers understand the systems' limitations, value attention reminders, and feel safer with safeguards that help sustain appropriate oversight (Mueller et al., 2022). Consistent with this, interview research indicates that while experienced drivers report that they may engage more in secondary tasks, they are likely adapting to the driving situation and identifying "safe" or less risky scenarios before engaging in those tasks (Lin et al., 2018). Recent human factors work also shows that users of Level 2 systems develop increasingly calibrated mental models over time, allowing them to integrate the system into driving in ways that ease cognitive demands without relinquishing supervisory responsibility (Huang et al., 2023). As a result, contemporary empirical evidence does not consistently support earlier thoughts that Level 2 driver assistance might produce widespread complacency; instead, evidence shows that drivers benefit from reduced workload, develop adaptive strategies, and can maintain engagement in ways that enhance, rather than undermine the safety case for Level 2.

In addition to human factors research, there have been several attempts across the late 2010s and early 2020s to assess the impact that Level 1 and 2 systems may have on crash rates. Unfortunately, unlike FCW, understanding Level 1 and Level 2 technology's impact on crash rates comes with several challenges. As described above, far fewer vehicles are currently equipped with Level 1 and Level 2 driver assistance, reducing any possible sample size in addition to the fact that these systems must be turned on by the driver and are advised to only be used in certain situations (e.g., on highways, or within specific operational domains; e.g., GM Super Cruise; Ford Blue Cruise). Regarding Level 1 technologies, researchers have suggested that ACC and LCA may have the potential to reduce crash risk (Tan et al., 2021a; 2021b; Aleksa et al., 2024). One study in China estimated that a 100% market penetration rate of ACC could reduce fatalities by as much as 5.48% and injuries by 4.91% (Tan et al., 2021a). Similarly, in their examination of lateral ADAS features, including lane departure warning (LDW), lane keeping assist (LKA) and LCA, PARTS found that MY 2020–2023 vehicles showed a reduction of 4% in single-vehicle road departures (PARTS, 2025).

A recent review comparing crash rates for vehicles equipped with Level 2 to those that are not equipped found that, although a number of studies found no differences in crash rates, likely due to small sample sizes, those that have all indicate a reduction in crash rates (Lennox et al., 2024). Although a recent IIHS study examining crash rates associated with Level 2 systems concluded that there is no convincing evidence that Level 2 systems are preventing crashes, it's important to note that the data show a trend of reduction of crashes (Cicchino, 2024; *Note:* This study does not examine driver engagement in the driving task). Given limitations

in sample size, as well as the inability to know whether a Level 2 system was engaged when crashes occurred within many of these crash studies, future work is needed to understand how the potential safety benefits of these systems are realized.

## CONCLUSION

Taken together, our review of the human factors literature and studies on crash rates to date indicate that Level 1 and Level 2 technology have potential for safety beyond that of a convenience feature. Early concerns regarding reduced engagement, attention, and increased secondary task activity have received mixed support, and several studies indicate that drivers often adapt to these systems and are able to maintain engagement while benefiting from reduced workload. For Level 2 systems in particular, conclusions regarding crash risk remain limited due to market penetration, sample size, and uncertainly about system engagement at the time of a crash. Given the current state of the technology and reduced proliferation as compared to other ADAS technologies, time, in addition to naturalistic and crash-based research with reliable system use information, is necessary to understand the true safety potential of Level 1 and Level 2 technologies.

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