28 Adapting Collision Warnings to Real-Time Estimates of Driver Distraction

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To control a vehicle in the dynamic roadway environment, a varying portion of the driver's attention must be allocated to the driving task. Under many circumstances, the flow of traffic may stabilize or disperse, making the following few seconds seem quite predictable and freeing the driver's attention to intermittently engage in nondriving activities for a few moments. Many tasks that are unrelated to driving may compete for the driver's attentional resources, such as talking with passengers, conversing on a cellular phone, or interacting with cellular phones or other nomadic devices. Even different driving-related tasks may compete with each other such that, while checking the blind spot, the driver is unable to simultaneously survey the forward road scene for potential threats. Drivers' expectations typically guide attention to potential threats in an efficient manner. Although many miles may pass without event, inevitably a situation will suddenly emerge that violates the driver's expectations. When such an unexpected and sudden situation develops, a driver may fail to devote sufficient attention to the roadway to support a timely and appropriate response. Collision warning systems can support the driver in these situations by directing the driver's attention to the unexpected or unnoticed situation on the roadway.

Data from actual driving suggest that unexpected situations can suddenly emerge and jeopardize driving safety if they coincide with a lapse in attention to the roadway. The results of the 100-car study imply that many crashes occur when the driver makes an inadequate response to an unexpected event just after the driver has been glancing away from the forward roadway.[1] Whereas the majority of noncollision lead-vehicle incidents* did not appear to be directly related to driver inattention, the linkage between "inattention to the forward roadway" and lead-vehicle crashes was compelling. In 11 of the 15 lead-vehicle crashes, the drivers' eyes were away from the forward scene just before or during the onset of the precipitating factors of the collision. Dingus et al.[1] suggests that inattention converted incidents into collisions by interfering with drivers' avoidance responses. This result indicates that inattention to the forward roadway is an important contributing factor in lead-vehicle and single-vehicle crashes, perhaps even to a greater extent than conventional collision statistics had implied (e.g., Ref. 2).

Although emerging technologies, such as nomadic devices and increasingly elaborate cellular phones, may interfere with the driving task, other innovations are being developed to enhance automotive safety. Many innovations have focused on improving the design of driver-vehicle interfaces to minimize driver head-down and hands-off-wheel time. Human factors principles have been applied to vehicle interface design to match the interface more closely to user expectations and abilities (e.g., Ref. 3). Such innovations are likely to reduce the demands of a given task substantially, such as dialing a phone number or reading a text message, but they do not directly address the timing of glances toward the in-vehicle technology in relation to the events on the roadway.[4] Another approach is needed.

One such approach is the development of safety-enhancing systems, such as forward collision warning (FCW) and lane departure warning (LDW), which are entering the automotive market. These systems support safety by warning the driver about immediate, unexpected conflicts. A major reason for the relatively slow introduction of collision warning systems into the passenger vehicle market is the potential rejection by drivers due to nuisance alerts. A system that drivers do not accept will provide no safety benefit. Both extended exposure to these systems on the road and relatively short exposures in the simulator suggest that nuisance alerts undermine driver acceptance (e.g., Refs. 5 and 6). Nuisance alerts often stem from the difficulty these systems have in detecting the driver's current state of awareness. For example, even if a system performs exactly as the designers intended and correctly identifies a potential threat associated with a slowing lead vehicle, attentive drivers may still view the situation as a nuisance alert. Whether a driver views an alert as useful or annoying depends on the driver's state of mind as well as the traffic situation. As a consequence, the next step in the adaptive-vehicle cockpit will be to measure not only the traffic situation, but also the driver's situation. To avoid annoying the driver, collision warning systems may need to adapt their warnings

* Lead-vehicle incidents were defined by Dingus et al.[1] as conflicts that required a crash-avoidance response that was smaller in magnitude than a rapid evasive maneuver but beyond the 99% confidence limit for a control input by the particular driver.

according to whether the driver is attending to the road or not. Such adaptive systems may greatly improve driver acceptance and safety.

Government-sponsored projects, that will evaluate the potential for adaptation to increase the effectiveness of conventional collision warning systems, are under way in both United States and Europe.[7] Whereas the European program Adaptive Integrated Driver-vehicle InterfacE (AIDE) has evaluated the concepts of adaptation to a host of different variables (e.g., driver preference, surface friction, and driver state; Brouwer and Hoedemaeker[8]; see also Chapter 26), the U.S. program (Safety Vehicles Using Adaptive Interface Technology, or SAVE-IT) has focused specifically on adaptation of collision warnings to the driver's state of distraction.[9–11] Although the results of the AIDE program appear to be relatively mixed for most types of adaptation, perhaps due to the extremely sensitive baseline collision warning algorithms,* the early results from the SAVE-IT program suggest that adapting collision warning systems to the driver's state may enhance the safety benefit of warning systems while simultaneously improving driver acceptance. This chapter explores how FCW and LDW systems have been adapted to take into account the driver's visual orientation.

28.1 VISUAL DISTRACTION AS A CATALYST FOR COLLISION

On global or national scales, automotive crashes occur with regularity, incurring significant costs and excessive human suffering. Severe crashes can produce devastating consequences, ending or changing forever the lives of the people involved. Automotive crashes are the most common cause of death for Americans between the ages of 4 and 34.[12] Yet for a single individual during any given mile of travel, the chances of a collision are extremely low. Although near-misses may be quite frequent, according to the National Highway Traffic Safety Administration (NHTSA) police-reported crashes in the United States occur on average only 2.1 times every million miles or once every 32 years of driving.[13] It appears that for many of these crashes to occur, a confluence of unfortunate circumstances must work together simultaneously.

As an extension of Heinrich's triangle,[14] Dingus et al.[1] argued that crashes are most often the result of the driver failing to adequately respond to a precipitating event due to various contributing factors. Figure 28.1 displays a simple model of lead-vehicle crash causation that is based on the observations of the 100-car study.[1] The central idea of this model is that crashes are typically caused when contributing factors, such as inattention or weather, interfere with an avoidance response to a precipitating event. When precipitating events (such as a lead vehicle unexpectedly braking) occur in the absence of the contributing factors, they are usually resolved by the flexible and adaptive response of the driver, resulting in what may be a near-miss, but usually not a collision. However, when contributing factors such as visual distraction are added, they act as a catalyst for a crash by interfering with the driver's response, converting a mere incident, or near-miss, into a collision. Other examples

* When the AIDE FCW and LDW systems were combined, drivers received alerts at a rate of approximately 70/h.

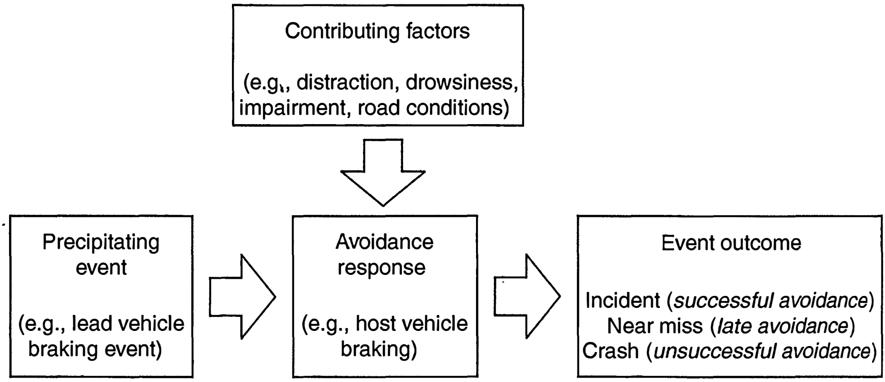

FIGURE 28.1 A simple model of distraction as a catalyst for collision.

of catalysts that can degrade driver responses might be poor roadway conditions, mechanical failure, and driver impairment due to fatigue, alcohol, or other factors.

This model is clearly an oversimplification and only considers the feedback of the driver in response to events rather than the ability of drivers to proactively drive in a manner to reduce risk. However, to the extent that this simple model approximates the reality of lead-vehicle or single-vehicle crashes, it would predict that, in the absence of a catalyst such as visual distraction, drivers are unlikely to benefit significantly from warnings. If the driver is attending to the forward roadway at the moment a precipitating event occurs, the driver usually detects the event and responds appropriately. In such a circumstance, there is usually little opportunity to improve the process. A collision warning would only present information to which an attentive driver is already aware. Even if the driver is visually attentive but is likely to react slowly due to age or intoxication, the warning system may still be unable to hasten the process, because ultimately drivers must confirm the threat for themselves before applying the brake.[6] The data presented in Figure 28.2 support this conclusion, showing that in this driving simulator study, drivers who were attentive to the forward scene released the accelerator at approximately the same time regardless of whether or how they were warned.[11] Although this situation was inherently threatening, with a collision rate between 10 and 15%, the collision warning system was unable to improve the response of visually attentive drivers.

It should be noted, however, that Lee et al.[15] found a different result in a similar experiment, in which a collision warning system eliminated the collisions which otherwise occurred at a rate of 14% for attentive drivers. This discrepancy may just represent differences in testing sensitivity or may stem from the relative ease with which drivers could see the lead vehicle in the Lee et al. study. The Lee et al. study used projectors of relatively low resolution and contrast, which may have made the deceleration of the lead vehicle relatively hard to detect and the benefit of the warning relatively great. Other factors that might contribute to the difference include the fact that the events in Lee et al. occurred at a lower speed than the SAVE-IT results showed in Figure 28.2 and the warnings were provided earlier. The discrepancy in these results demonstrates the importance of considering how drivers' perceptual capacity and attentional state interact with the onset of potential hazards.

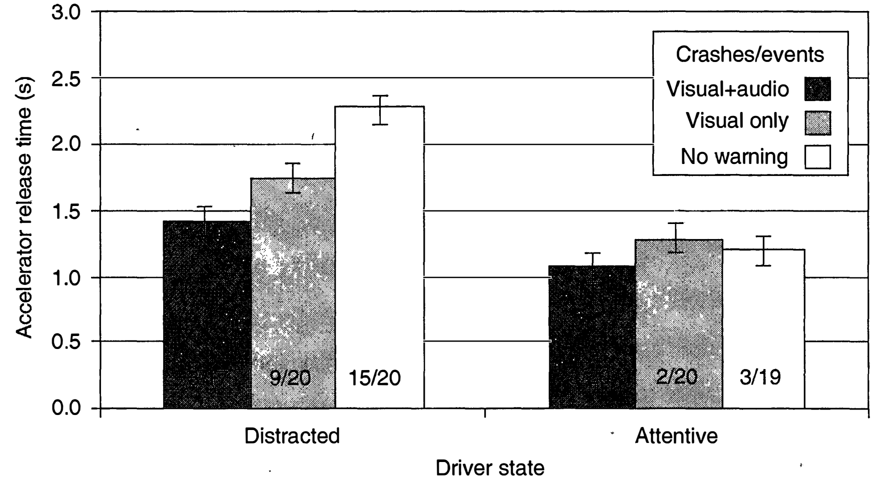

FIGURE 28.2 Accelerator release times and driving simulator crash rates of distracted drivers versus attentive drivers in the Safety Vehicles using adaptive Interface Technology program. Drivers were provided with either a visual-and-auditory, visual-only, or no forward collision warning alert. The bold numbers show the number of crashes/the number of events.

To the extent that FCW or LDW alerts are only useful for drivers who are not visually attending to the forward roadway, suppressing warnings when the driver's head pose is forward is likely to be an effective strategy for reducing nuisance alerts. In the context of the simple model shown in Figure 28.1, such an adaptive warning system monitors the essential ingredients for a collision, the precipitating event in the environment,* and the most common contributing factor that interferes with a successful avoidance response. By monitoring both environmental and driver facets of a potential collision, adaptive warning systems may provide alerts when drivers need them most while simultaneously reducing the overall rate of alerts.

If visually attentive drivers have little need for warnings, even when they are cognitively distracted, the strategy of suppressing alerts while the driver's visual attention is oriented to the forward scene is unlikely to compromise safety. The Collision Avoidance Metrics Partnership (CAMP) workload metrics project[16] data suggested that auditory-vocal tasks can actually lead to a reduction in the standard deviation of lane position (SDLP), supporting the conclusion that cognitive distraction does not degrade lane keeping.[11] The case for LDW may therefore be quite clear-cut: when an awake driver's visual attention is oriented toward the forward scene, if the vehicle is departing the lane, the driver is likely to be already aware of it. The optic flow specifying lane departure is extremely salient, and only deeply ingrained stimulus-response cognition is usually necessary for the driver to produce a counteracting response.

* For example, a lead vehicle braking or the host vehicle drifting out of the lane.

The extent to which FCW alerts may assist drivers who are cognitively distracted may be more uncertain. Many studies have demonstrated that cognitive distraction can have a detectable, yet relatively small, effect on driver reaction times to a lead-vehicle conflict.[17] Reyes and Lee[18] examined whether an auditory-vocal task increased driver reaction times to a lead-vehicle conflict. Although the impact of the auditory-vocal task was small for conflicts that could not be anticipated, when the conflict could be anticipated, the effect was far greater, increasing accelerator release times by as much as 600 ms. Reyes and Lee proposed that although auditory-vocal tasks had relatively little effect on the control level of driving, these tasks had a greater detrimental effect at the tactical level (see Chapter 5). Whereas cognitively attentive drivers were receptive to the clues that the conflict was about to occur, responding earlier when the clues were present, cognitively distracted drivers responded as if the clues were absent. Therefore, although cognitive distraction clearly has a smaller effect than visual distraction on a driver's ability to respond to rear-end conflicts, it is still uncertain whether FCW alerts are completely redundant for situations involving cognitive distraction alone (e.g., talking on a cellular phone). In the 100-car study data, two out of the 15 rear-end crashes occurred just after the driver appeared to be "lost in thought" or "daydreaming." It is difficult to predict whether an FCW system would have been successful in preventing these collisions, but this uncertainty may suggest that even if cognitive distraction cannot easily be measured, perhaps it should still be accounted for. For example, rather than suppressing an FCW alert completely in the absence of visual distraction, perhaps the alert should be softened or delayed.

28.2 FCW AND LDW COUNTERMEASURES

The U.S. Department of Transportation (DOT) has funded two large field operational tests (FOTs) to investigate the driver acceptance and potential safety benefits of FCW and LDW systems. The first of these was the Advanced Collision Avoidance Systems Field Operational Test (ACAS FOT) program that investigated adaptive cruise control (ACC) in combination with FCW.[6] In this program, 96 drivers used ACAS-equipped vehicles for a period of 4 weeks and a total of 137,000 miles. The FCW system used a forward-looking radar (FLR) to detect the range, range rate, and azimuth angle of several vehicles in front of the driver. When it appeared that the driver's vehicle needed to brake hard to avoid colliding with the lead vehicle, the ACAS system provided the driver with an icon on a head-up display (HUD) in conjunction with a series of rapid auditory tones.

During periods of manual (non-ACC) driving, FCW alerts were experienced at a rate of 14 alerts per 1000 miles. Analyses revealed that the alerts roughly broke down into thirds, including 36% of the alerts resulting from out-of-path events,* 32% of the alerts resulting from transitioning-path events,† and 27% of the alerts

* Out-of-path events were defined as situations wherein the target was never in the host vehicle's lane, and included mostly stationary objects, such as bridges and other objects either above the roadway or on side of the road.

† Transitioning-path events were defined as situations wherein a moving vehicle was is in the same lane as the host vehicle for some period of the conflict and out of the host vehicle's lane for another period.

resulting from in-path* vehicles. Determining which of these alerts was useful is an inherently subjective task that is likely to vary among drivers. Common types of nuisance alerts included situations where the host vehicle approached a lead vehicle that was vacating the lane (either turning or changing lanes) or when the host vehicle was approaching the lead vehicle with an intention to pass. By asking the drivers in the study to review alerts that were issued during their own driving experiences, the ACAS program revealed that usefulness ratings differed significantly between the three scenario types described earlier.[19] Whereas in-path events yielded alerts that were judged to be useful 53% of the time, only 33% of alerts that occurred in response to transitioning-path events were judged to be useful. Out-of-path events produced alerts that were judged to be useful only 14% of the time. Drivers' open-ended responses suggested that the level of perceived risk in these situations was often qualitatively different, even between in-path and transitioning-path events.

Using Lees and Lee's[5] terminology, this analysis suggests that a large percentage of the alerts were either unnecessary (alerts corresponding to situations judged as hazardous by the algorithm but not by the driver) or false (alerts corresponding to random activation of the system that does not correspond to a threat). Acceptance of the FCW system varied widely, with many drivers commenting that the rate of nuisance alerts contributed to their negative perceptions of the system. The two most frequent suggestions drivers made for improving the system were to reduce the rate of nuisance alerts and to allow the system to be turned off under certain circumstances.

A second FOT, the Road Departure Crash Warning System Field Operational Test or RDCW FOT was conducted using a similar design (78 drivers for 4 weeks) to investigate a LDW and curve speed warning system (CSW).[21,22] The CSW alerted drivers of a detected need to reduce vehicle speed in advance of a sharp curve. Unlike most LDW systems currently on the market, this system was more elaborate and featured not only lane-boundary sensing but also radar sensors to detect whether there was an obstacle beyond the lane boundary. The driver-vehicle interface for LDW used auditory cues for lateral movements of the vehicle over either solid painted lane markers or movements over dashed markers with an obstacle near that lane boundary. Haptic (seat vibration) cues were designed to give an impression similar to that of traveling over rumble strips. This alert occurred when the driver traveled over a dashed boundary with no detected obstacle. Common alerts, which might be considered to be unnecessary, included alerts when the driver knowingly strayed over the lane marker without consequence, or when the driver intentionally changed lanes without using the turn signal. Although the LDW alert rate per distance traveled was approximately six times greater for the RDCW FOT than it was for the ACAS FOT, these drivers provided more favorable acceptance ratings than the ACAS FOT drivers had for the FCW system.[22] Drivers of the LDW system also rated false alerts as having less utility than alerts in which they had drifted from their lane and later corrected their position.

* In-path events were defined as those wherein the host and lead vehicles occupied the same lane throughout the conflict. Almost all of the objects in this category were moveable targets (objects that the radar had previously seen to move).

One hypothesis for why the RDCW FOT yielded higher acceptance ratings for LDW than the ACAS FOT had yielded for FCW, in spite of the much higher alert rate, was that LDW is based on a criterion that drivers were able to understand and accept (crossing lane makers), compared with the FCW system, which could potentially leave drivers confused.* Whereas lane markers provide an unambiguous threshold that is visible to the driver for LDW, there is no immediately visible or universally agreed-upon threshold for FCW. Opinions about when an alert is warranted are likely to vary far less across drivers for LDW compared with FCW, and drivers can accurately predict when LDW alerts are likely to occur.

Perhaps as a result of the large amount of variability in these naturalistic studies, the two FOTs were unable to find a statistical link between nuisance alerts and driver acceptance. Lees and Lee (in preparation) examined the effects of nuisance alerts in a more controlled setting, manipulating the number of unnecessary alerts and the number of false alerts for an FCW system (see preceding definitions). In the context of this study, whereas systems prone to unnecessary alerts had relatively little effect on the driver's trust compared with a perfect FCW system, systems prone to false alerts reduced the drivers' trust compliance. Lees and Lee suggest that the predictability of the alerts is an important factor in determining both the trust in the system and the effectiveness of alerts. This result may imply that the ability to suppress some types of nuisance alerts may assist not only in improving system acceptance, but that this acceptance may, to some extent, determine the safety benefit of the warning system.

28.3 ADAPTIVE COUNTERMEASURES

When an FCW system does not take into account the driver's state, it cannot assume that the driver is completely attentive or completely distracted all the time. Driving simulator studies demonstrate that when a driver is distracted, single-exposure brake reaction times for unexpected lead-vehicle events often surpass 3 s.[9,15] Although far smaller mean reaction times (<1 s) have been recorded in test track events that were designed to surprise the driver (e.g., Ref. 23), these results likely reflect a heightened level of awareness due to the presence of an experimenter in the vehicle, the novelty of the test track, and the use of a surrogate target.† For this reason, it may be safer to assume that the upper bound for brake reaction times, which reflects a distracted driver who does not expect an event to occur in the next few moments, is closer to 3 s than it is to 1.5 or 2 s. Yet an FCW algorithm cannot invariably assume a brake reaction time of 3 s, because it would produce alerts at a rate that would both annoy drivers and degrade their confidence that the system provides anything other than false positives. But neither can an FCW system invariably assume that the driver will be able to react in less than 1 s. Such an assumption would likely result in a system that produces few nuisance alerts; however, when a necessary warning does occur, a distracted driver may require significantly more than 1 s to respond to avoid the collision.

* For example, alerts caused by overhead out-of-path objects such as signs or peripheral objects such as vehicles in other lanes or cones on the roadside.

† A research tool that appears as the rear end of a lead vehicle but is only a towed rear façade that is attached to a collapsible beam, capable of absorbing low-velocity collision impacts.

If the system cannot assume that the driver is either completely attentive or completely distracted and does not have access to data regarding driver state, it must adopt warning parameters that reflect the middle ground (e.g., a brake reaction time of 1.5 s). This middle ground represents a compromise between providing sufficient time for distracted drivers to respond while preventing an excessive rate of nuisance alerts. Because the nuisance alert rate is still likely to be greater than what many drivers are willing to accept, the selection of warning stimuli must similarly reflect a compromise between safety benefit and driver acceptance. Because of the high positive correlation between stimuli that are able to capture the driver's attention and those stimuli that annoy the driver,[20] rather than selecting warnings that are best able to quickly acquire the driver's attention, designers of the conventional warning system must select a set of less urgent stimuli, such as pleasant warning tones or subtle haptic seat pulses. The end result is a system that at best provides moderate safety benefit and produces moderate driver acceptance.[24]

Recent advances have allowed real-time driver-state monitoring technologies to evolve from a research tool into a system that is able to function within the constraints of the automotive environment. For several decades, driver-state monitoring technologies have existed as research tools, detecting driver drowsiness, head pose, and eye gaze. These technologies have typically been quite expensive, often costing as much as an entire vehicle, or have made requirements that are unreasonable for automotive applications, such as requiring physical contact with the driver. Reductions in the price of cameras and computing power are bringing the prices of these technologies down to a level that automotive consumers are more likely to accept and, in Japan, head-pose monitoring technology is now entering the automotive consumer market.[25]

The most common head-pose monitoring systems utilize computer vision algorithms that discriminate between a head pose that is forward or not forward. Further engineering development will soon provide head-pose monitoring technologies that will have relatively little impact on the cost of the safety warning countermeasures and may even allow for less expensive systems by reducing the requirements of external sensing. Because the SAVE-IT system utilizes head-pose monitoring technology to assess the driver's state of attention, the adaptive countermeasures discussed in this section adapt the state of the warning systems to the drivers' visual rather than cognitive distraction. Early experiments in the SAVE-IT program suggested that the techniques that are described in this section were not suitable for cognitive distraction and were thus applied to visual distraction only.[9]

The SAVE-IT program developed an initial list of adaptation strategies for the FCW and LDW systems (see Table 28.1) and selected the most promising candidates for more in-depth evaluation. The four adaptation strategies were Differential Display Location, Differential Display Modalities, Differential Alert Timing, and Alert Suppression. Whereas the Differential Display Location and Differential Display Modalities adaptations modify the nature of the driver-vehicle interface, the Differential Alert Timing and Alert Suppression adaptations modify the algorithms that generate the alerts. The Differential Display Location adaptation positions the visual stimulus of the alert in the location of the visual distraction to which the driver is currently attending, and the Differential Modalities adaptation provides a more

TABLE 28.1
Safety Vehicles Using Adaptive Interface Technology Program Positive and Negative Adaptation Strategies for Forward Collision Warning and Lane Departure Warning

Attention-Based Adaptation Strategy		Negative Adaptation—Attention Forward Goal: Improved Acceptance	Positive Adaptation—Attention Not-Forward Goal: Improved Safety
Nonadaptive		Nominal alert	Nominal alert
Modify human machine interface	Differential display location	Nominal alert	Visual alert in location of driver's attention
	Differential alert stimuli	Less intrusive or urgent stimuli	More intrusive or urgent stimuli
Modify algorithm	Differential alert timing	Later alert (less likely)	Earlier alert (more likely)
	Alert suppression	No alert	Nominal alert

urgent or attention-capturing stimulus when the driver is distracted. Whereas the Alert Suppression adaptation simply prevents alerts from being generated when the driver is attentive, the Differential Alert Timing adaptation modifies the likelihood that alerts will be generated, by providing earlier alerts when the driver is distracted and later alerts when the driver is not.

Most types of adaptation can be either negative or positive. Whereas negative adaptations diminish the warnings when the driver's attention is on the road, positive adaptations accentuate warnings when the driver's attention is away from the road. Specifically, adaptations in the "Attention Forward" column are negative, in that they feature methods for suppressing or softening alerts, and the modifications under the "Attention Not-Forward" column are positive adaptations, in that they include methods for accentuating or promoting the alerts. The primary goal of negative adaptation is to improve driver acceptance by reducing the potential nuisance of unnecessary and false alerts. Although unnecessary alerts are targeted more directly by the negative adaptations, the reduction in the overall number of alerts during the attentive periods of the drive will also significantly decrease the rate of false alerts. The primary goal of positive adaptation is to improve the safety benefit of the warning systems. Although the primary goals are separate for negative and positive adaptation, the dimensions of driver acceptance and safety benefit are not independent. For a system to be successful in achieving a safety benefit, the driver, to some extent, must accept the alerts. Lees and Lee (in preparation) demonstrated that drivers complied less with their FCW system when the system was prone to false alerts. This "cry wolf" effect has been consistently shown to undermine response to warning systems.[26–28] Furthermore, it is likely that if the system apparently fails to achieve a safety benefit, drivers may be less likely to accept the system because they do not perceive the system as being useful.

28.3.1 Differential Display Location

The Differential Display Location adaptation strategy modifies the placement of the alerting visual stimulus as a function of the driver's focus of attention. In the

SAVE-IT example of this adaptation, when the drivers were distracted by their interactions with center-console applications and either the FCW or LDW systems produced an alert, the safety warning systems presented a visual warning stimulus (an FCW or LDW icon) on the center console, temporarily replacing the material that was currently being displayed. This icon was presented redundantly with the other visual-and-auditory stimuli only when the driver was already interacting with the center console, so that if the driver was attending to the forward roadway, only the conventional visual-and-auditory warning stimuli appeared. The rationale for this adaptation is that if the driver glances at the center console, an alert icon placed in the center console is more likely to acquire the driver's attention, thus increasing the utility of the visual stimulus. The reason that warning icons should not be indiscriminately positioned in the center console is that positioning an icon away from the frontal location is likely to draw the driver's attention away from the external threat. This adaptation attempted to circumvent this problem by only presenting an icon in the center console when the driver's attention was already away from the forward scene. As shown in Table 28.1, drivers who were attending to the forward scene at the time of the alerting event received a nominal (nonadaptive) warning. Although this type of adaptation appears to be reasonable, SAVE-IT testing suggests that it is not beneficial to the driver. Perhaps the center-console icon delayed the drivers from returning their gaze back to the forward scene, and thus the subsequent decision to brake.

28.3.2 Differential Display Modalities

Like the Differential Display Location adaptation strategy, the Differential Display Modalities strategy operates by modifying the driver interface of the FCW and LDW systems. In the SAVE-IT program, this adaptation modified the interface by providing a visual-only alert when the driver was attending to the forward scene and a visual-plus-auditory alert when the driver was not. The reasoning behind this strategy is that drivers who are already looking in the forward direction are likely to be able to detect a visual alert located near the forward scene and thus may not need the auditory stimulus. Whereas, drivers with a forward head pose may be adequately alerted from an orientation-dependent stimulus (such as a visual alert), distracted drivers may require an orientation-independent stimulus (such as an auditory alert) to reacquire their attention. An auditory alert is more likely to produce annoyance than a visual stimulus because it is usually more intrusive than a visual stimulus and cannot be localized to the driver, thus potentially interrupting conversations or undermining the passenger's confidence in the driver. The Differential Display Modalities adaptation seeks to reduce annoyance by suppressing the most intrusive component of the alert, which is usually the auditory component, when the driver is attentive to the forward roadway.

In the initial phase of the SAVE-IT program, this strategy not only used a negative adaptation of suppressing the auditory component of the alert, but also provided a positive adaptation by providing a voice stimulus (saying "lead vehicle braking" or "drifting left" or "drifting right") at an early threshold when the driver was attending to the forward scene. This particular type of positive adaptation (using voice stimuli) was quickly dismissed after the experiment demonstrated that it led to excessive driver annoyance; however, other, less annoying, alternatives might be conceived. The data in Figure 28.2 imply that when drivers attend to the forward roadway, neither the visual nor auditory stimuli are likely to provide a significant benefit. Although this result may represent a lack of sensitivity rather than an actual lack of a difference, it suggests that the opportunity to benefit attentive drivers is relatively small. Thus, rather than supporting a Differential Display Modalities strategy, it seemed to suggest that the strategy of suppressing the alert entirely (Alert Suppression) may be viable.

One potential benefit of Differential Display Modalities adaptations is that they may be able to help reveal the underlying functionality of the warning system. For example, rather than completely suppressing an LDW alert when the driver is unlikely to require it, an LDW system might only suppress the more intrusive auditory component, still providing a more private haptic (e.g., seat vibration) stimulus. That way, even though the auditory stimulus is suppressed and drivers are saved from the potential annoyance, the core LDW system functionality is revealed, and drivers will still be able to observe that the system detected the lane crossing. It also allows for the possibility of providing some benefit for drivers who are severely cognitively distracted or drowsy if such drivers are able to benefit from the warnings. Whereas the total suppression of an alert when the driver is visually oriented to the forward scene would not provide assistance for drivers' states other than visual distraction, Differential Display Modalities adaptations still provide an alert to drivers who are oriented to the forward scene. These alerts may potentially benefit a driver who is visually attentive but whose response may be degraded in some other way (e.g., cognitive distraction), even though the other source of degradation is not identified. In this way, the Differential Display Modalities adaptation may accommodate other types of degradation that cannot be measured.

28.3.3 Differential Alert Timing

The Differential Alert Timing strategy provides earlier alerts for distracted drivers and later alerts for drivers who appear to be attentive to the forward scene. In the first phase of the SAVE-IT program, the Differential Alert Timing strategy was applied to both the FCW and LDW systems. Whereas the FCW algorithm was adapted by altering the assumed driver brake reaction time in response to the alert, the LDW system was adapted by narrowing the thresholds for lane crossings. This strategy is based on data demonstrating that distracted drivers require more time to respond to an alert than attentive drivers (e.g., Refs. 9 and 15). By providing differential predictions for how quickly a driver will respond to the warning, an FCW algorithm can provide distracted drivers with sufficient time to respond and prevent a large percentage of unnecessary alerts from being given to attentive drivers.* SAVE-IT research demonstrated that the rate of nuisance alerts could effectively be reduced by later timing when the driver was attentive (negative adaptation), and that early alerts for distracted drivers could reverse the negative effects of distraction (positive

* Attentive drivers are likely to respond to the threatening conditions, or the fleeting pseudo-threat is more likely to dissipate before the alert threshold is reached.

adaptation). Like Lee et al.'s[15] results, the SAVE-IT program demonstrated that earlier warnings translated into significantly earlier responses, with distracted drivers who experienced the earlier alert* braking 2.3 s after the lead vehicle braking event compared with the nominally alerted distracted drivers who began braking 3.1 s after the event.[11]

28.3.4 Alert Suppression

Alert Suppression is perhaps the most simple and obvious negative adaptation strategy, and it directly governs whether the warning is issued rather than the manner in which it is issued. When the driver attends to the forward roadway, the alert is suppressed, but otherwise the alert functions like a nominal warning system. Figure 28.2 implies that the safety benefit of an FCW system is compromised little by suppression of alerts when the driver is attentive to the forward roadway. One potential shortfall with the Alert Suppression strategy for FCW is that it does not allow FCW alerts to provide benefit in situations other than when the driver is visually distracted. When the driver's visual attention is forward, regardless of the driver's cognitive state, the alert will be suppressed. Alert Suppression may be a better candidate for LDW systems. The data collected during the SAVE-IT program suggest that drivers who are attentive to the forward roadway receive no benefit from an LDW system.[11] Even without an LDW system, attentive drivers reacted so quickly to a simulated wind gust in a driving simulator experiment, that there appears to be little room for improvement. A wind gust that was quite threatening to distracted drivers simply did not pose a threat to the drivers who were not engaged in a secondary task. Many drivers corrected with the lateral disturbance so rapidly that they did not even notice the wind gust at all.

The SAVE-IT program evaluated the Alert Suppression strategy in a small on-road study. In this study, 14 Delphi employees† drove a vehicle for 160 miles each, experiencing an adaptive LDW system for half of the time and a nonadaptive LDW system for the other half.‡ The adaptation suppressed 95% of the alerts, with the 14 drivers experiencing a total of 81 alerts (78 alerts per 1000 miles) while the system was in nonadaptive mode and only 4 alerts (4 alerts per 1000 miles) while the system was in the adaptive mode. Participants indicated that the adaptive system produced alerts at a rate that was more likely to be acceptable, and 12 of the 14 participants preferred the adaptive system to the nonadaptive system. The remaining two drivers, who preferred the nonadaptive system, indicated that they preferred the consistency of receiving alerts every time that they crossed the lane. Further subjective measures suggested that these drivers might have preferred a Differential Display Modalities adaptation that suppressed only the auditory component when they were attentive. Although the system only employed a negative adaptation technique, participants

* When the driver was distracted the adaptive FCW algorithm assumed a 3-s reaction time, compared to a 1-s reaction time for a nonadaptive algorithm. The earlier reaction time assumption translated to an alert that was provided 2 s earlier for the adaptive system.

† Employees were screened so as to exclude those who worked on products related to LDW or driver monitoring.

‡ The order of the trials was counterbalanced.

indicated an average rating* of 3.9 for the adaptive system in response to the statement "the LDW system enhances on-road safety" compared with an average rating of 3.1 for the nonadaptive system.

For the FCW system, the SAVE-IT program selected a version of the Differential Timing strategy that, on the negative side of adaptation (alert reduction), was quite similar to an Alert Suppression strategy. Rather than suppressing an alert outright, the alert timing was implemented in such a way that only in rare circumstances would drivers with a forward head pose receive an alert. By selecting a short brake reaction time (0.5 s), the FCW system could prevent the vast majority of nuisance alerts from occurring while the driver was attentive to the forward scene. Yet in rare cases, where an attentive driver could potentially benefit from an alert, a late alert was still able to occur. The SAVE-IT program also evaluated the adaptive FCW system in comparison with a nonadaptive FCW system in a small on-road study. In this study, 14 drivers experienced the two versions of the FCW system over a total of 1698 miles. Unlike the adaptive LDW system, the adaptive FCW system could provide alerts in some circumstances that might not have occurred in the nonadaptive baseline condition (due to the earlier timing during nonforward head poses). Whereas the nonadaptive system produced a total of 64 alerts (75 alerts per 1000 miles), the adaptive system produced 19 alerts (22 alerts per 1000 miles), representing a 70% reduction in alerts. Out of the 13 of 14 participants who indicated a clear preference, 10 participants preferred the adaptive mode to the nonadaptive mode. Whereas eight of 14 participants indicated that more than 50% of the nonadaptive alerts were a nuisance, only two participants indicated that the adaptive nuisance alert rate was greater than 50%. Participants also indicated more favorable ratings for alert timing and greater likelihood to recommend the system to others. Surprisingly, even though the FCW adaptive system featured both positive and negative adaptations, and the LDW system only featured negative adaptation, unlike the LDW system, participants rated similarly the extent to which the adaptive and nonadaptive systems enhanced safety.

28.4 CONCLUSIONS AND FUTURE CONSIDERATIONS

The future of adaptive collision warnings is likely to be primarily influenced by two factors: the driver state–sensing technology and the marketing of adaptive systems to consumers. As sensing technologies provide increasingly accurate and sensitive information about the state of the driver, the methods for adaptation will likely evolve to make use of the new information. For example, whereas head pose provides a coarse indication of visual distraction only, future systems will provide information about where the driver's eyes are focused. This more fine-grained information will likely support the detection of both cognitive distraction (Reyes and Lee[28]) and driver intention.[30] Although the price of automotive-grade technology with sufficient resolving power to support the detection of cognitive distraction may currently be excessive, such technology is likely to become increasingly affordable,

* The questionnaire used a four-point scale (1-strongly disagree, 2-somewhat disagree, 3-somewhat agree, 4-strongly agree).

soon providing adaptive systems with information regarding the driver's cognitive state (see Refs. 29–32). Increased resolving power is also likely to support the detection of driver impairment due to alcohol or other drugs in the near future. The adaptation techniques that were reviewed in this chapter did not appear to be suitable for the presentation of collision warnings when drivers are cognitively distracted[9]; however, more subtle and sophisticated techniques may be developed to make use of this information regarding the driver's cognitive attention. One of the challenges of adapting collision warning systems to the driver's cognitive state may be that, whereas the criteria for a driver's visual orientation might be easily observed and understood, the criteria for more complex phenomena such as the degree to which the driver is mentally engaged in the driving task may be more subjective and less easily understood by the driver.

The extent to which drivers accept adaptive collision warnings may also be influenced by how these systems are marketed to the public. Drivers who have an inadequate understanding of the system might perceive the warning behavior as inconsistent when an alert is provided in one instance (when the driver's head pose is *not* forward) but not in another (when the driver's head pose *is* forward). Such drivers might view this system as failing to provide a safety benefit. If unnecessary alerts do not degrade trust in the system,[5] drivers may prefer to witness alerts, even when the system may be able to predict that the alert will be unnecessary. Drivers who understand the concept of adaptation may prefer a system that provides a subtle alert (e.g., haptic or visual-only) when they are attentive rather than one that suppresses the alert completely, because it may continue to reinforce that the system is providing the protection and is accurately detecting the lane change or the lead vehicle braking. The recent SAVE-IT results suggest that drivers who have adequate knowledge of how the system is intended to operate may appreciate that their own behavior is taken into account when the system decides when to issue an alert. The driver's mental model is thus a crucial factor in determining the acceptance of different adaptation techniques. How an adaptive system is perceived or which type of adaptation is preferred may therefore be highly dependent on how these systems are marketed or how they are sold on the showroom floor.

Adaptive collision warning systems face a challenging trade-off. Without adaptation, the systems are likely to warn drivers unnecessarily or fail to warn drivers in a timely manner. As a consequence, trust and acceptance may decline. With some types of adaptation, drivers may feel that the system operates in a capricious and arbitrary manner, a feeling that also leads to a decline in trust and acceptance. The theoretical basis of trust may offer a way to manage the trade-off.[31] Trust depends on the driver's assessment of the performance, process, and purpose of a system. For collision warnings, performance depends on the number of warning failures. Adaptation could enhance the performance basis of trust. For collision warnings, the process basis of trust depends on the driver's ability to understand the algorithms and mapping between environmental conditions and the warning occurrence. Adaptive systems involve more complex algorithms and so may undermine the process basis of trust if they are not implemented carefully. For collision warnings, the purpose basis of trust depends on the driver's understanding of why the system was developed and that the complexity of adaptive warnings could impact this basis in an unpredictable manner. To achieve the greatest possible benefit of adaptation, the next generation of warning systems must carefully consider all three bases of trust, perhaps using a combination of the different positive (accentuating) and negative (diminishing) adaptation alternatives.

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