A Pilot Study on Mitigating Run-Off-Road Crashes

Final Report

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16. Abstract (Limit: 250 words)

Run off the road crashes account for approximately 50% of motor vehicle related fatalities on a national and on a state level. To address this unacceptably high rate of fatalities this pilot project first sought to identify the primary factors associated with run off the road crashes and identify limitations and shortcomings of existing countermeasures. This was accomplished through the development of a taxonomy that summarized existing engineering related and human factors related literature according to infrastructure, environment, and driver related factors that have been found to be most associated with run off the road crash-related fatalities. Based on the taxonomy results a new potentially useful countermeasure was identified that consisted of a haptic and auditory feedback. The pilot project then sought to develop and then evaluate a series of prototype countermeasure systems based on haptic and auditory feedback presented either individually or in parallel. The primary results of the driving environment simulator study in which participants drove through a series of realistic worlds experiencing the countermeasures in response to lane departure events found that the presentation of multiple countermeasure systems can provide increased user satisfaction but can also increase driver response times to critical situations. Secondary results of the study suggest that the haptic countermeasures can provide additional information to drivers but that it may not be interpreted by drivers as expected by designers.

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Executive Summary

In Minnesota, 395 individuals were killed in traffic crashes in 2012 and of those crashes 52% were the result of a run-off-road (ROR) crash (Minnesota Crash Facts, 2012). Similarly, single-vehicle ROR crashes in 2009 accounted for approximately 53% of all fatal crashes in the United States (Fatality Analysis Reporting, 2009). The cause of these types of crashes can be attributed partially to environmental factors (e.g. curves, lane/shoulder width, surface conditions, and speed limits), but are more often attributed to driver-related factors (e.g. error, distraction/inattention, fatigue, drug/alcohol consumption, and aggressive driving).

While substantial steps have been taken to flatten curves, widen roads/shoulders, impose barriers, and remove collision-prone objects, ROR crashes consistently account for nearly half of all fatal crashes. The introduction of rumble strips to notify drivers of an impending lane departure has spurred other methods of notifying and preventing lane departures via in-vehicle systems (e.g. auditory/visual warnings and haptic/tactile alerts). While these Lane Departure Warning Systems (LDWS) show some promise in successfully warning drivers of impending lane departures, their ability to appropriately capture attention, convey information, and guide an appropriate response must still be refined to consistently prevent ROR crashes. Haptic warnings presented through the seat or steering wheel have an advantage of swift comprehension by drivers and steering wheel torque can simultaneously indicate the direction in which the driver should steer to return to one's lane; however, research has indicated that drivers perceive torque as too intrusive.

The purpose of this pilot study was to review the literature to examine the factors that contribute to ROR crashes and identify gaps in the literature, identify current and promising future countermeasures to reduce the occurrence of ROR crashes, and to conduct a pilot study examining the utility of a promising countermeasure. This pilot study hypothesized that torque would be a superior LDWS compared to other methods, but drivers would rate it poor with respect to usability because of its abrupt onset and strong intensity. Additionally, this pilot study proposed that perceptions of poor torque usability could be ameliorated by presenting additional haptic warnings prior to torque onset and decreasing the intensity of the signal while maintaining its effectiveness. Participants were tested in 3 separate experimental groups to determine the effectiveness of the various LDWS in avoiding ROR crashes and system user satisfaction compared to no warning. Group 1 tested haptic warning systems (torque, seat pan, and seat back) presented individually, at full intensity. Group 2 tested dual LDWS (seat pan+torque and seat back+torque) presented sequentially, at medium intensity compared to medium intensity torque and control conditions. Group 3 tested triple LDWS (seat pan+seat back+torque and seat back+seat pan+torque) presented sequentially, at lower intensities compared to low intensity torque conditions.

Contrary to the research identified in the review of literature, results of the pilot study revealed that the individual LDWS did not differ in response times, but did reveal faster response and re-entry times for younger drivers compared to older drivers. The sequential countermeasure presentations (dual LDWS, and/or triple LDWS) did not reveal additional differences between individual and dual LDWS, however the single torque countermeasure resulted in quicker responses than the triple LDWS method. The results suggest that multiple countermeasures,

despite being presented sooner in the countermeasure cycle, did not decrease driver response time or the amount of time out of lane. These findings suggest that multiple presentations of information did not reduce or impede driver response compared to singular countermeasure presentations; however, subjective ratings of the torque only condition compared to two or three countermeasure presentations was less preferred by participants although not all significant. Moreover, the intensity of the torque was decreased in sequential countermeasure presentations and achieved similar reaction and recovery times suggesting a less intrusive, but equally effective torque is possible when primed with other haptic countermeasures prior to its activation.

The results suggest additional research that can integrate haptic feedback from in-vehicle countermeasure systems with infrastructure related technologies (e.g., rumble strips) in an effort to create a combined infrastructure/driver performance mitigation technique would be beneficial and have potentially better user acceptance of such systems. Furthermore, the addition of information to the review of literature and review of infrastructure specific techniques can be valuable next steps in investigating ROR mitigation techniques.

Chapter 1. Introduction

A run-off-road (ROR) crash occurs when a single vehicle departs the roadway to the left or right and then collides with another vehicle, collides with an obstacle on or off the roadway, or rolls over after exiting a roadway. The severity of these crashes is evidenced by recent data indicating that the average fatality rate for ROR crashes between 2007-2009 accounted for approximately 53% of all fatal crashes in the United States (FHWA Roadway Departure Strategic Plan, 2013) and approximately 52% of all crash fatalities in Minnesota in 2012 (Minnesota Crash Facts, 2012) (see Figure 1). As a result, ROR crashes account for the highest rate of fatalities and injuries when compared to all other crash scenarios (e.g., intersection collisions, rear end crashes) and, as evidenced by Figure 2, the rates of ROR crashes has remained relatively stable in the previous eight years of available data (Minnesota Crash Facts 2004-2012). It is because of the high rate of fatalities and injuries associated with ROR crashes that it is necessary to identify factors contributing to these crashes and to develop countermeasures to reduce their prevalence.

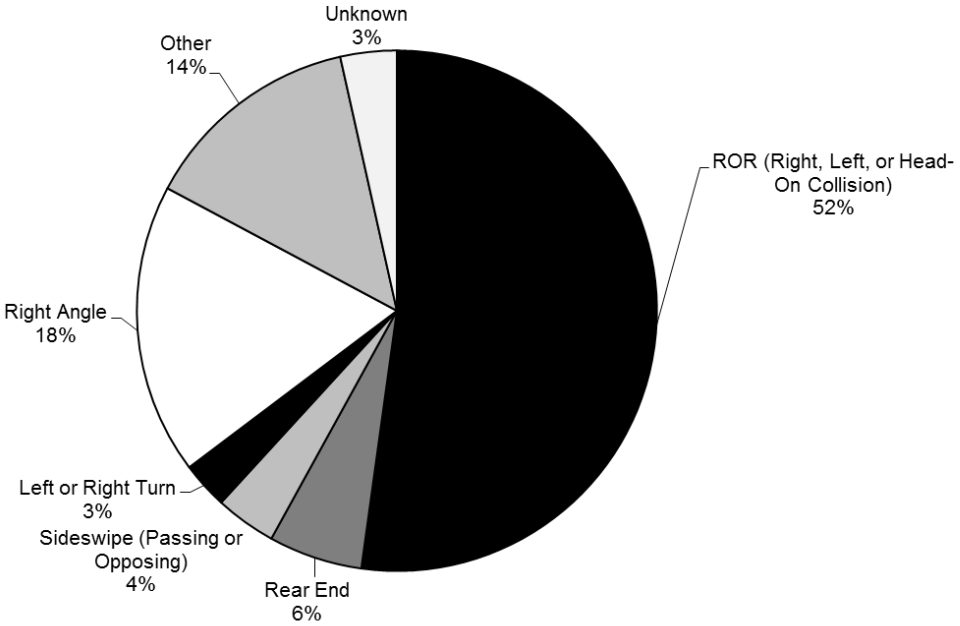


Figure 1: Amount of run-off-road crashes compared to other crash types in Minnesota for 2012.

With this goal in mind the research team conducted an ambitious pilot project consisting of three phases. The first phase consisted of reviewing existing scientific literature that identified the array of factors contributing to ROR fatal and injurious crashes. The second phase reviewed existing literature and engineering trends to identify current ROR countermeasures and to identify technological gaps that could be exploited to address the ROR problem. Particular focus was directed at identifying those ROR countermeasures related to the infrastructure (e.g., roadway geometry) and driver behavior (e.g., fatigue) because of the increased potential for influencing these factors. As an example, while infrastructure techniques (e.g., rumble strips)

have seen a benefit and reduction in ROR events, alternative driver behavior warning methods may be a ubiquitous way of reducing ROR events from a vehicle perspective.

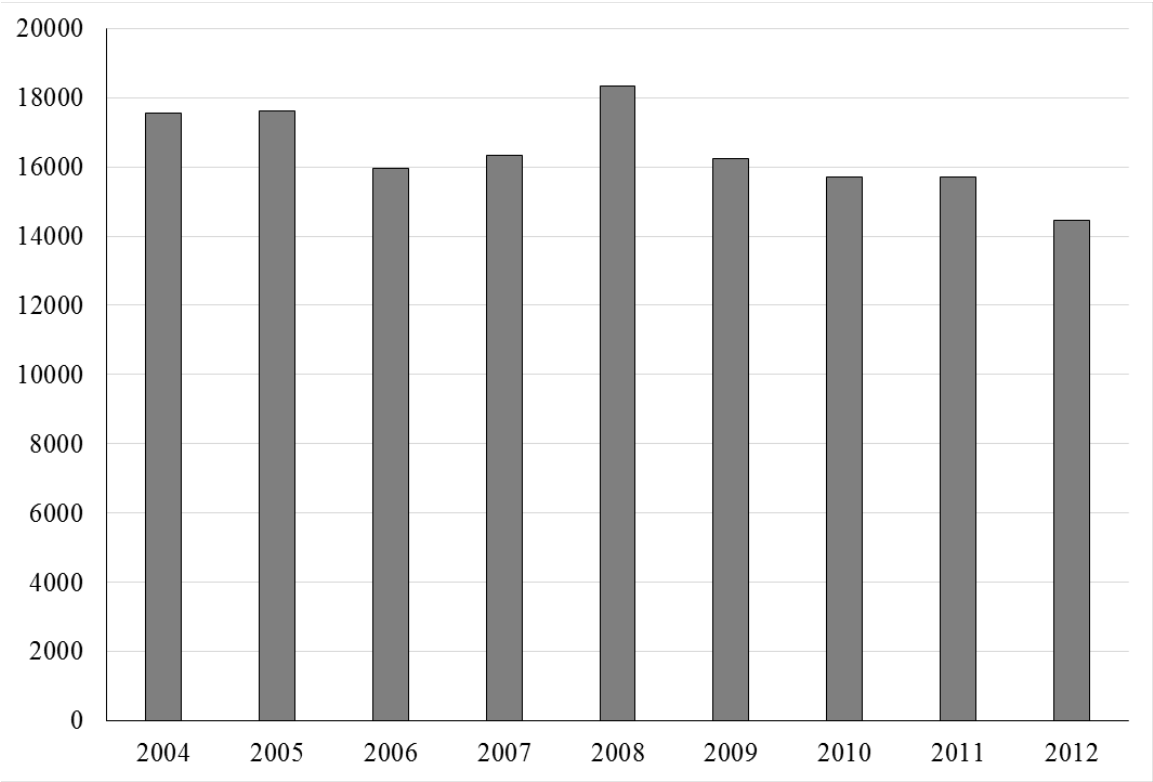


Figure 2: Total number of run-off-road crashes for Minnesota from 2004 to 2012 (Fatal, Injury, and property damage).

Information gained from the first two project phases informed the selection and development of technology-based ROR countermeasures that were evaluated within the third phase of this pilot project. Specifically, the research team examined ROR countermeasures that provided drivers with information about ROR events through force changes in the steering wheel and through vibro-tactile motors installed in the driver's seat. These countermeasures represent new and promising methods of informing drivers of ROR events that could have a marked influence on fatal and injurious rates of ROR crashes.

This technical report summarizes the project effort in five main sections that include:

- Introduction
- Run Off Road Contributing Factors
- Run Off Road Countermeasures
- Countermeasure Evaluation
- Study Discussion
- General Discussion and Conclusions

Chapter 2. Run-Off-Road Contributing Factors

The first phase of the pilot project consisted of reviewing and briefly summarizing existing scientific literature that identified the array of factors contributing to fatal and injurious ROR events. The next step was to identify gaps in the scientific literature that could be explored in the research portion of this project (Phase 3).

Previously, research efforts focused primarily on the *types* of ROR events (e.g., AASHTO Report 500: Volume 6, 2003) that were associated with fatalities and injuries that included ROR events such as single vehicle roadway departure and head-on collisions. While this type of information is certainly informative it provides little or no information regarding the underlying *causal factors* that may have been associated with the initiation of the event. Causal factor information is important because it can be employed by transportation safety professionals in the development of infrastructure, vehicle, or driver-based ROR countermeasures that address directly the factors that may be promoting ROR events.

The review of literature was conducted by scanning published articles in transportation safety journals (e.g., Accident Analysis and Prevention, Human Factors, Transportation Research Part F), technical reports produced by federal and state agencies (e.g., FHWA, NHTSA, MnDOT), and technical reports produced by private agencies (e.g., AAA FTS, CAMP). Where findings overlapped between sources we cited the most recent source. Given the large volume of information that could be generated from such a review of literature we chose to summarize the primary findings into a series of taxonomies. Each taxonomy classified information into a series of groups or categories. The process began at a macro level where the general source of an ROR event may have occurred. The focus was then directed towards contributing factors for ROR events within each macro level. The examination of the literature through this method also allowed the research team to identify gaps and additional areas of interest that could be pursued during the research phase of the project. The review of literature was not meant to be exhaustive but rather to briefly summarize primary factors contributing to ROR crashes that may be considered for the development of ROR countermeasures within later phases of this project.

Two main sources of ROR events emerged from the review of literature activity. The first source included infrastructure/environmental factors (external to the vehicle) and associated infrastructure mitigation techniques. The second source, driver factors, related to the driver as a source of ROR events and included subcategories as cognitive factors, physical/motor responses, and visual information. The following sections summarize the review of literature findings according the macro levels and macro level subcategories created within the taxonomy. A research citation and brief summary of the primary findings are presented for each category to limit the size of the current report.

2.1 Infrastructure and Environmental Factors

The review of literature indicated that numerous infrastructure and environmental factors are thought to contribute to ROR events. As an example, subtle changes in the roadway alignment on roadways with higher speed limits may contribute to higher rates of ROR events. The primary infrastructure and environmental factors identified via the review of literature are identified in Table 1.

Table 1: Infrastructure/Environmental factors contributing to ROR crashes.

FACTORS	LITERATURE	CONCLUSIONS
Road alignment	Lord et al., (2011), Liu & Subramanian (2009), Neuman et al. (2003), Zegeer et al. (1987).	Changes in alignment (both vertically and horizontally) increase the likelihood of an ROR crash. Among the crashes that occurred on curved roads, 90.2 % of them were ROR crashes, while among those that occurred on straight roadways, 62.1% were ROR crashes.
Roadway function class	Liu & Subramanian (2009), Neuman et al. (2003)	Among all crashes that occurred on rural roadways, 80.6 % of them were ROR crashes, while among the crashes that occurred on urban roadways, 56.2% of them were ROR crashes.
Speed limit	Lord et al., (2011), Liu & Subramanian (2009), Davis et al. (2006).	Over half of the crashes reported for the study by Lord et al. (i.e., 197 of 393 in total) involved speeds greater than the posted limit prior to the roadway departure. Among all the crashes that occurred on roadways with posted speed limits of 60 mph and above, 81% were ROR crashes; among the crashes that occurred on roadways with speed limits less than 60 mph, 69% of the vehicles were ROR crashes.
Time of day/lighting	Liu & Subramanian (2009), Najm et al. (2003)	Among the crashes that occurred during nighttime (8 p.m. – 5:59 a.m.), 74.2% were ROR crashes; among those crashes that occurred during the day time period (6 a.m. – 7:59 p.m.), 66.5% were ROR crashes.
Weather conditions	Liu & Subramanian (2009)	Among the crashes that occurred in adverse weather conditions, 75.5% of the crashes were ROR crashes; among those crashes that occurred in good weather conditions, 70% were ROR crashes.

The research cited above identified, like previous research efforts, that rural ROR crashes are particularly problematic. It was also found that high speeds, poor weather conditions, and nighttime driving were also significant factors contributing to ROR crashes (Liu & Subramanian, 2009; Patel et. al., 2007). Interestingly, straight roads were a significant factor associated with ROR crashes, however, we speculate that the rate of crashes is higher on straight roads partially due to the fact that a larger percentage of roadways share this classification. As a result, roadway alignment could be considered a factor associated with ROR crashes. It should be noted that driver-related factors contributing to ROR crashes, such as fatigue, may be exacerbated by straight roads that lack appropriate cognitive stimulation. These factors were identified as important elements and, as a result, were considered for inclusion in the research portion of this project.

2.2 Driver Factors

The infrastructure and environmental ROR crash causation factors provided one perspective of the ROR crash factors. A second perspective focusing on driver factors is essential because

results from allied research found that 95% of the factors for ROR crashes were attributed to drivers while only 5% were attributed to vehicle or environmental factors (Liu & Subramanian, 2009). These data tentatively suggest that further efforts to understand ROR crashes and the development of successful ROR countermeasures that focus primarily on driver factors may yield the greatest reduction in ROR crash rates.

The review of literature of driver related factors indicated that decrements in driver performance could be categorized according to cognitive, perceptual, motor/physical factors. These factors were of particular focus because information gained about them could be used to directly inform the configuration of existing and future ROR countermeasures that would directly address driver related factors contributing to ROR crashes.

Results of the review of literature on general driver factors indicated that driver sex and age were significant factors. As an example, of all fatal single-vehicle crashes involving men, 72% were ROR crashes, whereas of all fatal single crashes involving women only 66.5% were ROR crashes (Liu & Subramanian, 2009). Drivers between the ages of 20 and 30 were more likely than older drivers (60 through 70 years old) to be involved in ROR crashes, specifically left lane departures. A unique data set from Iowa indicated that middle-aged drivers were more likely to be involved in ROR events than older drivers (Hallmark, Boyle, and Qiu, 2012).

Driver cognitive factors were those factors that influenced or were influenced by differing states of cognitive functioning (see Table 2 for a summary of the driver cognitive factors examined for this project). Driver inattentiveness was identified as the primary driver cognitive factor contributing to ROR crashes because it accounted for 85.4% of all single-vehicle ROR crashes. In comparison, of the single-vehicle crashes that did not involve inattention, only 57.1% of those were ROR crashes. This statistically significant comparison is also practically significant because it suggest that ROR countermeasures should seek to improve attentiveness or seek to capture attention just prior to or during an ROR event. There are other driver cognitive factors that are significantly more difficult to incorporate into the design of ROR countermeasures. For example, alcohol consumption (as indicated by a blood alcohol content of .01 or higher) and driver fatigue were significantly associated with ROR crashes (Liu & Subramanian, 2009) but they are factors that may be addressed more successfully through education, outreach, and training avenues.

Table 2: Driver cognitive factors influencing ROR events.

FACTORS	LITERATURE	CONCLUSIONS
Fatigue/sleeping	Liu & Jianqiang (2011)	The odds of being involved in a ROR crash for a fatigued driver was 3.48 time greater than the odds for a non-fatigued driver.
Inattentiveness	Liu & Subramanian (2009)	85.4% of single-vehicle crashes in which drivers were inattentive were ROR crashes, while only 57.1% of single-vehicle crashes that did not involve driver inattention were ROR crashes.
Stress	Liu & Jianqiang (2011)	Among single-vehicle crashes in which the driver was feeling some type of work-related stress or pressure, 86.4% were ROR crashes. Only 59.5% were ROR crashes among single-vehicle crashes in which the driver was not feeling work-related stress or pressure.
Auditory distractions	Wood et al. (2006)	Participants were told to either listen to words or both listen to words and repeat them. Increased auditory complexity decreased performance.
Mental workload	Shanmugaratnam (2008)	Participants who drove a simulator in high workload situations were more likely than those in low workload situations to have crashes, fail to scan intersections, and deviate farther from the lane position.
Working memory problems	Ball, Owsley, Sloane, Roenker, & Bruni (2009)	Found that older drivers who are severely restricted in their useful field of view are six times more likely to have been in a car crash in the past five years than older adults whose useful field of view are not restricted. May be due to working memory problems.

In addition to cognitive influences on ROR events, the frequencies of ROR crashes are a result of inappropriate or inaccurate driver perceptual responses (it should be noted that there can be large

overlap between driver perceptual and cognitive factors associated with ROR events). Table 3 summarizes those situations where driver perceptual factors contribute to ROR events.

The review of literature findings examining driver perceptual failures such as attentional tunneling, auditory distractions, visual impairments, and reduction in UFOV all contribute to reduced lane guidance adaptation and a potential to miss salient cues to maintain lane position. These impairments suggest that the addition of an in-vehicle visual countermeasure may be not be effective or may be counterproductive in the presence of an actual ROR event. Using an auditory feedback countermeasure technique may also serve as a distraction and therefore may be counterproductive for reducing the rate of ROR events. These results suggest that it may be beneficial to identify and develop ROR countermeasures that inform drivers via non-visual and non-auditory feedback channels.

Table 3: Driver perceptual factors influencing ROR events.

FACTOR	LITERATURE	CONCLUSIONS
Deficit in selective attention	Ball, Owsley, Sloane, Roenker, & Bruni (2009)	Older drivers who are severely restricted in their useful field of view are six times more likely to have been in a car crash in the past five years than older adults whose useful field of view are not restricted. May be due to deficit in selective attention.
Perceptual or attentional tunneling	Wood et al. (2006)	Perceptual or attentional tunneling was caused by cognitive distraction. Increased level of visual distraction was associated with slower reaction times, poorer driving performance, and a decreased UFOV.
Inattention blindness	Strayer, Drews, & Johnston, 2003	Drivers talking on a cell phone are more likely to fail to stop at an intersection and more likely to be involved in rear-end collisions than drivers not using a cell phone. No difference found between hands-free headsets and regular cell phones. Suggests that using a cell phone creates inattention blindness.
Inaccurate surveillance	Romoser and Fisher (2009)	Older adults are less likely to visually scan side-to-side prior to entering an intersection. Found evidence that this was due to cognitive factors, not physical factors.
Attentional failures	Romoser & Fisher (2009)	Found that attentional failures may be caused by cognitive decline, decreased situational awareness, and/ or decreased scanning behaviors.
Central RORs	Wood et al. (2006)	Found that auditory distractions resulted in more central RORs.
Peripheral RORs	Wood et al. (2006)	Found that visual distractions resulted in more peripheral RORs.
Deficit in situational awareness	Ball, Owsley, Sloane, Roenker, & Bruni (2009)	Deficits in situational awareness include decreased rate of visual information processing and deficit in selective attention.
Visual sensory impairment	Romoser & Fisher (2009)	Found that older adults are less likely to visually scan side-to-side prior to entering an intersection. Found evidence that cognitive decline may lead to decreased situational awareness and scanning behaviors.
Decreased rate of visual information processing	Ball, Owsley, Sloane, Roenker, & Bruni (2009)	Found that older drivers who are severely restricted in their useful field of view are six times more likely to have been in a car crash in the past five years than older adults whose useful field of view are not restricted. May be due to decreased rate of visual information processing.

A final contributing factor identified in the review of literature was that of erroneous physical or motor responses that led to ROR events. These included, for example, over-correcting when a lane departure was occurring, poor directional control, and incorrect evasion technique. Table 4

provides a general overview of those factors identified as part of the ROR taxonomy. The identification that driver physical and motor responses contribute to ROR events suggests that the development of ROR countermeasures should focus on driver responses to ROR events in addition to providing drivers with countermeasures that improve attention and reduce distraction. These types of ROR countermeasures might include in-vehicle systems that can detect the nature and extent of a driver response, determine response appropriateness, and then initiate vehicle control (e.g., corrections) to reduce ROR event severity. While these countermeasure offer much promise for addressing ROR events it is unlikely they will be developed and deployed in the near and mid-term future due to complexity in predicting driver responses and the high cost of system development.

Table 4: Driver physical/motor responses influencing ROR events.

FACTOR	LITERATURE	CONCLUSIONS
Over-correcting of vehicle	Liu & Jianqiang (2011), Hallmark et al. (2009)	14.3% of driver-related reasons for ROR crashes were attributed to over-correcting of the vehicle, less so for commercial vehicles (e.g., 5%)
Panic/freezing	Liu & Jianqiang (2011), Hallmark et al. (2009)	0.3% of driver-related reasons for ROR crashes were attributed to panic or freezing – 0.1% for commercial truck drivers.
Poor directional control	Liu & Jianqiang (2011), Hallmark et al. (2009)	12.6% of driver-related reasons for ROR crashes were attributed to poor directional control. 6.5% for commercial truck drivers.
Incorrect evasion	Liu & Jianqiang (2011), Hallmark et al. (2009)	3.3% of driver-related reasons for ROR crashes were attributed to incorrect evasion, 2.6% for commercial truck drivers.
Illegal maneuvers	Liu & Jianqiang (2011)	0.1% of driver-related reasons for ROR crashes were attributed to illegal maneuvers.

2.3 Summary

The review of literature provides an initial view of the cognitive, perceptual, and motor responses that contribute to ROR events. The primary findings from this effort suggest the following:

- ROR crashes on rural roadways are overrepresented.
- Speeding contributes to ROR crashes, such that higher speeds have higher ROR crash rates.
- A number of infrastructure countermeasures have been implemented, but cost/benefit and asset management of infrastructure solutions may be cost prohibitive in some cases.

- The primary cognitive factors that influence ROR events include fatigue, inattentiveness, and distraction.
- Perceptual declines associated with age can contribute to an increase in reaction times (i.e., poorer), increase in attentional failures, and a restriction in situation awareness. These factors can also be linked to inattentiveness. The effects of perceptual declines are compounded when paired with reduced attentional resources and information processing capabilities.
- Over-correcting and poor directional control can contribute to a higher rate of ROR crashes, however, addressing these factors is hindered by the lack of appropriate understanding of driver responses and the high cost of the development and deployment of systems to address these factors.

Chapter 3. Run-Off-Road Countermeasures

Phase one of this pilot project consisted of a review of relevant literature examining the array of infrastructure/environmental and driver related factors contributing to fatal and injurious ROR crashes. Results of Phase One indicated that infrastructure/environmental factors such as rural two lane roadways and driver related factors such as inattention and poor responses to an ROR event can contribute to the unacceptably high rate of ROR crash related fatalities and injuries. The results begin to indicate that several of the factors (e.g., inattention, distraction) can be addressed by ROR countermeasure through improved driver feedback and warnings while other factors (e.g., poor driver responses to ROR events) are more difficult to address.

The purpose of Phase Two was to review and briefly summarize the existing scientific literature to identify any new or insufficiently examined ROR countermeasure that may significantly reduce ROR fatalities and injuries. We employed taxonomies that categorized the review of literature results into infrastructure/environmental countermeasures and driver countermeasures. Similar to Phase One, the review of literature was not meant to be exhaustive but rather to briefly summarize primary countermeasures in these areas so that underutilized but promising ROR countermeasures could be identified. To accomplish this the research team scanned technical reports and articles published by transportation safety journals, federal and state agencies, and private agencies.

3.1 Infrastructure and Environmental Countermeasures

Engineers have applied, with varying success, a number of different countermeasures to negate the environmental and driver related factors that contribute to ROR events. An initial approach to minimize the occurrence of ROR events was to employ infrastructure-based countermeasures (see Table 5). These included countermeasures such as flattening and widening side slopes to prevent rollovers, eliminating shoulder drop-offs, providing skid-resistant pavement to increase traction, flattening curves, and installing shoulder and center lane rumble strips (which create a vibration in the vehicle, alerting the driver to the fact that he or she has crossed over a lane). Another factor that led to an increased severity of ROR crashes was the likelihood of colliding with a stationary object (e.g. pole, tree) off the road after a ROR event. To reduce the severity of ROR crashes, objects are removed or relocated away from particularly high-risk areas.

The variety of the infrastructural improvements employed has yielded some promising reductions in ROR crashes. The FHWA conducted a before-after research effort using Highway Safety Information System (HSIS) data for intersections in Illinois. The report identified a reduction in single vehicle rural ROR events by a total of 21.1% with a decrease in injury accidents of 7.3% (FHWA, 1999).

The infrastructure and environmental countermeasures review of literature indicated that these countermeasures could have a marked impact on reducing the rate of ROR crashes. These positive findings are encouraging but should also be placed within a larger transportation safety context that acknowledges their true potential. In particular, it is noted that ROR crash rates have failed to decline significantly from 2004 to 2009 (FHWA Roadway Departure Strategic Plan, 2013), thus suggesting that the benefits of infrastructure and environmental

countermeasures may have been maximized and, as a result, it is necessary to develop and deploy new ROR countermeasures.

Table 5: Infrastructure/Environmental mitigation countermeasures.

COUNTER-MEASURES	LITERATURE	GOALS	CONCLUSIONS
Rumble strips on shoulder	Neuman et al. (2003), Patel et al. (2007), Lord et al., (2011)	The goal was to prevent vehicles from leaving roadway. It has a low cost to implement and a short time frame to do so (less than a year).	Identified that rumble strips could reduce ROR crash rate by 20-50 percent. Reduction in Minnesota ROR events by 13 percent.
Shoulder widening and paving	Neuman et al. (2003), Lord et al. (2011).	The goal was to prevent vehicles from leaving roadway.	ADT impacts the effectiveness of shoulder widening. One study noted an ROR reduction of up to 50 percent with a 4ft widening. Nominal width extensions (e.g., 2ft) can reduce crashes by 4%.
Reduction of pavement edge drops	Lord et al (2011), Hallmark et al., (2006).	The goal was to prevent abrupt drop-off when vehicles depart roadway and eliminate re-entering problems.	Drop-offs greater than 2-inches promote increased severity of crashes. Providing sloped pavement edge promotes easier roadway re-entry.
Removing trees/poles in high-risk areas	Neuman et al. (2003).	The goal was to minimize the likelihood of crashing into an object. It has a low cost to implement and a short time frame to do so.	Increase in clear zones reflected decreases in crashes. For example, clearing an additional 5ft reduced crash likelihood of 13%.
Enhanced delineation on road curvatures	Neuman et al. (2003).	The goal was to prevent vehicles from leaving the roadway. It has a low cost to implement and short time frame to do so.	Increasing roadway curve delineation reduced the ROR crashes rate by 15%.
Enhanced pavement markings	Neuman et al. (2003), Lord et al., (2011)	The goal was to prevent vehicles from leaving the roadway. It has a low cost to implement and a short time frame to do so.	Effective in highlighting the lane edge and may reduce ROR crashes by 10-15%.
Maintaining/improving existing guardrails	Lord et al., (2011)	The goal was to reduce the severity of the crash. It has a moderate to high cost to implement and a medium length time frame to do so.	Decrease in collision speeds from 50-75 percent thought to aid ROR crashes, presents an additional roadside object.

3.2 Driver Performance ROR Countermeasures

Driver performance ROR countermeasures are those that focus on changing or supporting driver performance through the provision of different sensory information. These countermeasures can provide visual, auditory, and/or haptic information or warnings to which a driver is expected to respond. For example, as a driver crosses an edge line they could be provided with visual information in the form of a flashing icon to indicate a ROR event is underway. Similarly, when a ROR event is detected by a vehicle-based system a driver could be provided with an auditory tone, provided with vibrations via the seat pan or seat back, or could be provided with haptic feedback in the form of steering wheel vibrations.

The review of literature of driver performance ROR countermeasures found a surprising number of studies examining the use of different sensory modalities, and, to a lesser extent countermeasures, to inform or warn drivers of an impending or ongoing ROR event. Table 6 provides a brief summary of several prominent studies. The table indicates the type of modality implemented, the associated publication citation(s), and summarizes the countermeasure type and associated results.

Table 6: Driver performance ROR countermeasures for left and right ROR events.

MODALITY TYPE	LITERATURE	COUNTERMEASURE RESULTS
1. Multilevel Tactile (a) 2. Unilevel Tactile (a) 3. Control (b)	Enriquez el al. (2001)	1. Tactile response was produced by varying pulsations of varying frequencies on the driver's hands through inflatable pads. RT lowest on average for vibratory stimulus with multi-levels compared to single level. Multilevel stimuli present, no missed event. 2. RT faster than when no haptic stimuli were present. Stimuli present, no missed events; stimuli not present, multiple missed events; however the # of incorrect responses increased when the haptic stimuli was present. 3. No inflatable pad haptic stimuli present to provide countermeasure.
1. Auditory 2. Haptic (Wheel Vibratory Countermeasure) 3. Motor Priming (MP) 4. Haptic (Seat Vibratory Countermeasure) 5. Auditory & Motor Priming (AMP)	Navarro, Mars, Forzy, Jaafari, & Hoc (2010)	1. A sound was broadcasted through a loudspeaker placed on the door of the simulator on the side of the ROR. Subjectively ranked the highest, had slower response times compared to AMP/MP. 2. Two vibrators were inserted in the upper part of the steering wheel (one on each side). The active vibrator indicated the side of the ROR. Similar response times to Auditory warning, ranked below Auditory for subjective assessments – conveyed no meaning. 3. An asymmetric steering wheel oscillation was generated. Torque was stronger (2 N/m, 100 ms) in the direction of the lane center and weaker (0.5 N/m, 200 ms) in the direction of ROR. The period of the oscillation was 300ms. Fastest (with AMP) response times, ranked the lowest subjectively (with

		AMP). 4. A set of vibrators was placed on each side of the seat. The active vibrators indicated the side of the ROR. Comparable response times to auditory, unfavorable subjectively. 5. The auditory and motor priming devices were combined and triggered at the same time. Fastest (with AMP) response times, ranked the lowest subjectively (with AMP).
1. Vibrotactile	Ho, Tan, & Spence (2005)	1. A tactor belt was used. One tactor was placed on the middle of the participant's stomach; the other was placed on the middle of his/her back. Response times were faster and more accurate when responding to spatially cued directions (front/back).
1. Auditory 2. Haptic 3. Auditory & Haptic	Stanley (2006)	1. The simulator generated auditory signals through the car's internal speakers using a "rumble strip" sound. Average response times were longer for a non-directional warning (1.24 s) compared to a directional sound warning (1.14 s). Both results are slower than Haptic. 2. The simulator was equipped with the IVIBE® Tactile Feedback Seating Unit. When the participant reached the specified threshold the bottom portion of the seat vibrated. General haptic warning had slower response times (0.92 s) than directional haptic warnings (0.89 s). 3. A combination of the two was used. For all 3 types, the countermeasure persisted as long as the driver was past the lane boundary threshold. Combined warnings were faster than auditory alone and for a not directional warning (1.04 s) compared to a directional warning (1.23 s).
1. Single & Graded Haptic (+Visual) 2. Single & Graded Auditory (+Visual)	Lee, Hoffman & Hayes (2004)	1. For the haptic countermeasure, the front seat was modified to include actuators on the front edge and in the thigh bolsters of the seat that vibrated to generate the haptic cues. Graded warnings induced maximum deceleration events – suggesting cautionary breaking. Haptic graded warning and single warning "preferred" over auditory counterpart. * The visual countermeasure was an icon presented on a screen which was mounted on the dash of the car in a head-down position (it appeared for all conditions). 2. The auditory countermeasure consisted of sounds at the severe level (74.3dB), moderate level (62.5dB) and negligible level (53.7dB). Graded warnings induced high mean deceleration events. Auditory warnings ranked lower than haptic counterparts. ** No statistical differences found for warning modality.

1. Tactile (steering vib) 2. Motor priming 3. Auditory (beep-mono) 4. Auditory (beep-stereo) *All warning types presented with and without prior meaning of warning explained (unpredicted/predicted)	Suzuki & Jansson (2003)	1. Entire steering wheel vibrated. Had the fastest response times in unpredicted and similar to other warnings for predicted scenarios (0.52s** and 0.43 s, respectively). Highest ranked subjectively. 2. Force torque (2Nm, 3 Hz) to position the vehicle back to center lane. Authors do not call it motor priming but rather tactile force torque. Next fastest results for unpredicted and similar to other warnings for predicted (0.72 s** and 0.44 s). Ranked lowest subjectively. 3. Both front dashboard speakers produce auditory beep sound at 78 dB. Second slowest in unpredicted (1.19 s)**and faster in predicted (0.38 s)**. 4. Speaker on the side of the event produced auditory beep sound at 78 dB. Slowest response times in unpredicted (1.36 s) and comparable response times for unpredicted (0.38 s). Auditory warnings ranked average subjectively. ** Low number of participants in unpredicted results (n=6).
1. Tactile & Motor Priming (MP) 2. Auditory & Motor Priming (MP) 3. Visual & Motor Priming (MP) 4. Motor Priming (MP) 5. Control	Kozak et el. (2006)	1. Steering wheel vibration was a 15 Hz vibration with 2Nm peak amp for 1.5 s and was paired with steering wheel torque. This combination resulted in the fastest response times (0.46 s). 2. Rumble strip noise presented to driver. The aural warning was also paired with the steering wheel torque (MP method). The rumble strip countermeasure and MP had the next fastest response time (0.55 s). Countermeasure had highest subjective ratings and most liked. 3. HUD used by illuminating a row of flashing red LEDs mounted on top of the panel and reflected onto the driver's field of view on the windshield. Wheel torque presented as well in combination with this one. Had the next fastest response time but increased variability (0.58 s). 4. Wheel torque presented to the driver to indicate the correct angle required in order to return to the lane. Had the slowest response times compared to all countermeasures (1.02 s) and had lowest subjective ratings. 5. No countermeasure presented. Yielded highest RT. Only significantly different to tact/mp countermeasure ($p<0.05$). Aud/MP approaching sig ($p=0.06$).

A number of techniques have been implemented previously that incorporate visual, auditory, and haptic methods in an effort to orient driver's attention back to the roadway environment and

notify them of the impending situation. While many of these techniques overlap between research efforts, the results are incongruent between similar countermeasure techniques. Of particular interest was providing drivers with a modality that conveys information quickly to reduce response time to an event. The use of haptic warnings appears to give drivers fast and appropriate information, depending on the research effort, however some implementations were still inconclusive due to methodological issues or unexpected outcomes. Furthermore, how drivers respond to these countermeasure methods in terms of appropriate actions and acceptance of the countermeasure type varies considerably and requires additional investigation. The different countermeasure modalities combined with the influence of the previously described factors allowed the research team to further investigate haptic methods and multiple countermeasure techniques as part of the driving simulator experiment.

3.3 Summary

The review of literature provided an initial review of the primary infrastructure/environment and driver performance ROR countermeasures examined within scientific publications. Particular emphasis was directed toward identifying auditory, tactile, and haptic ROR countermeasures that may be useful for reducing ROR crashes in the future. The prominent findings indicate that:

- Mono-aural warnings capture attention but provide little additional information to aid drivers in identifying the cause of the countermeasure activation.
- Stereo auditory warnings added response time when presented initially to participants indicating the effort to process and search for the corresponding meaning is not worth it.
- Furthermore, pairing auditory, visual, and haptic methods provide mixed results that are not consistent across the research efforts.
- Haptic warnings provide fast and comparable responses by drivers to warned events. However, some haptic methods are preferred over others.
- Single presentations of countermeasures vary based on sound level, visual information, and force of haptic feedback and are inconsistent across research efforts.
- The torque countermeasure appears to provide promising response times but also suffers from mixed results between research efforts. The results include fast response times, but poor understanding of the countermeasures results poor rankings. Reducing the intensity of the countermeasure may yield different results.
- Finally, little research has been completed identifying if sequential haptic countermeasures can provide comparable or better response for drivers.

These factors, explored within the context of the review of literature, provide the foundation for the pilot driving simulator study that was conducted in the final phase of this project. The research highlighted that motor priming (steering wheel oscillations) provided a fast response time, but was not well received by drivers. Haptic countermeasures appear to be well-received by drivers, but do not provide clear directional feedback compared to motor priming/torque feedback. However, a combination of these countermeasure techniques has the potential to orient driver attention to the ROR event and in critical situations provide a motor priming response that provides a directional cue for drivers. Finally, providing scenarios that coincide with higher ROR crash rates (e.g., rural roadways, single lane, and higher speeds) will provide situation specific scenarios to investigate ROR crash mitigation techniques. These elements from the taxonomy

feed directly into the simulator investigation conducted as the next logical phase in the entire research effort.

Chapter 4. Countermeasure Evaluation

4.1 Introduction

ROR crashes account for approximately half of all fatal crashes in Minnesota (Minnesota Crash Facts, 2012) and in the United States (FHWA Roadway Departure Strategic Plan, 2013). A reduction in crashes of this type would have a significant effect on lowering the rates of serious injuries and fatalities in Minnesota and across the country. As indicated in the Run-Off-Road Factors and Run-Off-Road Countermeasures sections of this report there are a variety of factors that can be attributed to ROR crashes. As a result, addressing ROR crashes can be a complex problem.

Efforts to reduce serious injuries and fatalities due to ROR crashes using infrastructure solutions have focused on keeping drivers in their lane and by reducing the impact of a crash once a driver has departed the roadway. Preventing a lane departure before it occurs is the most ideal solution to address ROR crashes. These prevention efforts are commonly implemented through improving road alignment by flattening or eliminating curves which account for approximately 90% of ROR crashes (Liu & Subramanian, 2009; Neuman et al., 2003; Zegeer et al., 1987), reducing speed limits, widening lanes/shoulders, and implementing rumble strips. Enhanced delineation of sharp curves holds promise for reducing ROR crashes (Neuman et al., 2003) although this is an expensive and not always feasible implementation. Providing drivers with additional time to correct their trajectory and lane position before fully departing the roadway also has a positive impact on reducing crashes and has been successfully accomplished through speed reduction, lane widening, and shoulder widening (Neuman et al., 2003; Lord et al., 2011). Perhaps the most recognized lane departure prevention method is rumble strips on the shoulder and centerline of roads. While this lower-cost method is effective in capturing the attention and improving response times of drowsy or distracted drivers (Corkle, Marti, & Montebello, 2001), it has little impact on lane departures caused by other factors, such as loss of control, skidding, speeding, and possibly drunk drivers thus it may be necessary to explore alternative ROR countermeasures.

When prevention methods fail to keep drivers in their lane, intervening infrastructural solutions can also deployed to minimize the severity of a potential ROR crash. Despite the fact that a ROR crash typically involves only one vehicle, the dynamics of a crash can be diverse due to the variety of outcomes resulting from a driver leaving their lane, e.g. colliding with fixed objects, colliding with other vehicles, or experiencing a rollover. Potentially the most obvious method for lane departure intervention is placing physical barriers to block vehicles from leaving the roadway or crossing the centerline. A variety of barriers have been tried including the cost and space demanding concrete buffer medians, steel guardrails, and the lower cost cable median barriers (Lord et al., 2011). While concrete medians impose tremendous impacts for colliding passenger vehicles due to their rigid state, cable median barriers are a safer solution for vehicles due to their flexible nature; conversely, cable median barriers may be more dangerous for motorcycles due to their tendency to ‘snag’ motorcyclists limbs (Berg et al., 2005). Another approach has been aimed at reducing or removing the fixed objects, such as trees or poles, near the roadway to minimize the risk of a driver colliding with a stationary object; however, there can be resistance from the public regarding environmental changes and, more importantly,

removing light poles that pose additional risks by reducing visibility at night (Neuman et al., 2003). Finally, reducing the pavement edge drops and implementing safer slopes/ditches can reduce rollovers and crashes by minimizing the transition for drivers departing and re-entering the roadway; however, this method is costly and time intensive (Lord et al., 2011; Hallmark et al., 2006).

While various road conditions tend to be more dangerous and are more likely to be the site of ROR crashes (i.e. curves), approximately 95% of ROR crashes are attributed to driver error (Liu & Subramanian, 2009). These errors are due to various factors, but commonly include driver impairment (i.e., distraction, inattention, fatigue, sleeping, and drug and alcohol consumption), medical conditions, and improper control of the vehicle (e.g. speeding, over-correcting, following too closely, poor control, incorrect or illegal maneuvers, and aggressive driving; Liu & Jianqiang, 2011). A wide variety of in-vehicle countermeasures have been designed and tested to reduce the rates of ROR crashes since so many are caused by preventable driver behaviors. These in-vehicle countermeasures can be classified into two main groups: Lane Departure Warning Systems and Lane Keeping Systems. The more prevalent of the two, Lane Departure Warning Systems (LDWS), notify drivers of an impending lane departure in an attempt to capture the driver's attention in time for a corrective maneuver to be enacted to keep the vehicle in lane or on the roadway. The second and less prevalent of the two, Lane Keeping Assist Systems (LKAS), similarly warn drivers of a lane departure, however, if no corrective action is taken, the vehicle uses some level of automation (i.e., steering and braking) to take control of the vehicle to prevent a ROR crash (Wu, Chiang, Perng, Lee, & Chen, 2005). A majority of the LDWS and LKAS products rely on computer vision (e.g., Mobileye) to detect lane markings or patterns to gauge the driver's position and determine if the vehicle is exiting the lane. Despite marked improvements in computer vision in the past decades, these systems face limitations on roadways with poor or no road markings and are not reliable in inclement weather (i.e., rain or snow) or at night.

LDWS currently available in the marketplace lack a consistent method for notifying drivers of a lane departure. The presentation types can be divided into three main categories: auditory, visual, and haptic. Commercially available LDWS typically employ a pulsed auditory tone (i.e. beep) through the vehicles' speakers to capture drivers' attention; however, alternative auditory presentations have also been tested, including audio of simulated rumble strips (Kozak et al., 2006; Navarro, Mars, & Hoc, 2007; Stanley, 2006), verbal indicators (e.g. "curve, curve", Sayer, 2005), car horn (Ho, Spence, & Tan, 2005), as well as skidding tires and European sirens (Jenkins, Stanton, Walker, & Young, 2007). Auditory warnings tend to have modest promise in reducing ROR crashes because they can capture the attention of drowsy or inattentive drivers. Visual warnings are typically presented in tandem with an auditory or haptic warning and can vary from flashing rows of LEDs above the dash (Kozak et al., 2006), information presented via HUD, and visual icons displayed on a screen (Lee, Hoffman & Hayes, 2004). Visual warnings do not have the same ability to capture the attention of drowsy and inattentive drivers as do auditory and haptic warnings, the visual channel is already taxed with constant driving information, but visual warnings do provide an opportunity for presenting redundant information to improve detection and comprehension.

Both auditory and visual warnings can be presented in directional form to indicate to the driver which side of the road they are departing to spur an appropriate response; however, the comprehension-to-action speed may be slower than desired to avoid a ROR crash. Haptic warnings, (e.g., presented through the seat pan, seat back, or steering wheel) present warning through a vibrotactile interaction so a driver would "feel" a tactile sensation. Furthermore, haptic warnings offer a unique opportunity to capture the attention of drivers and provide directional information. Similar to auditory or visual warnings, however, traditional haptic warnings of these kinds do not provide clear information to the driver regarding the appropriate response to the signal. One method to address this issue is to present drivers' with a motor priming signal by using force torque to pull the steering wheel back toward the center of the lane (Suzuki & Jansson, 2003).

4.2 Haptic Countermeasures

4.2.1 Haptics

Providing haptic countermeasure feedback through in-vehicle support systems has several advantages over other sensory modalities. First, the countermeasure information is provided through a sensory channel that is underutilized compared to the visual and auditory channels (Lees et al., 2012; Ho et al., 2005; Van Erp and Van Veen, 2004; Sklar and Sarter, 1999). Second, the information presented through specific haptic systems (i.e., steering wheel) have been found to be comparable to other modalities to reduce response times to critical events (Navarro, Mars, Forzy, Jaafari, and Hoc, 2010; Navarro, Mars, and Hoc, 2007; Suzuki and Jansson, 2003). The utilization of haptic feedback as part of an in-vehicle support system may allow the opportunity to significantly enhance driver safety and warning system effectiveness.

Providing an in-vehicle countermeasure through an alternative modality is an attractive alternative for addressing ROR crashes. Haptic warnings can be provided a number of different ways, but usually involve embedding actuators or placing tactors within a vehicle component that has direct physical contact with a driver. Fenton (1966) provides an early example of delivering haptic feedback to drivers. Participants performed a car following task with a control stick in a driving simulator. The control stick operated the functions of the vehicle simulator (e.g., left, right, accelerate, and brake) and the head of the control stick provided headway feedback and relative velocity information through a protruding tactile slider. As headway distance decreased the slider was pushed out which conveyed the reduction in distance to the lead vehicle. Though the use of this rudimentary tactile feedback participants' headway and the corresponding relative velocity decreased and then remained consistent compared to a control condition with no feedback. Overall, the tactile information was understood by drivers and paved the way for addition in-vehicle haptic support systems.

Recently, more advanced in-vehicle haptic countermeasures have been provided through the vehicle steering wheel, seat pan, seat back, and foot pedals. Janssen and Nilsson (1993) provided haptic feedback to drivers through a "smart" gas pedal that provided a continuous force when a drivers' headway was at or below a defined threshold. Other warning methods were utilized (i.e., auditory and visual), but only the haptic pedal provided safety benefits by reducing the number of headways below 1 second that were experienced by drivers. Tijerina et al. (2000) also saw positive benefits for a haptic pulse brake pedal for potential rear-end collision situations (e.g.,

stopped vehicle ahead). In their experiment drivers were signaled to brake based on the initiation of the pulsing brake pedal. Driver's braked "harder" and applied greater pressure as the intensity of the brake pulse increased, reducing braking response time and distance. Furthermore, Lee, Hoffman, and Hayes (2004) tested graded countermeasure warnings in a simulated car following scenario. The warnings included haptic, auditory, and visual components and activated when the lead car braked suddenly. When comparing reactions to the braking event, warning modality was not significantly different. However, the graded haptic warning was received more favorably than the auditory warning and had comparable response times. Positive subjective ratings are an important factor when paired with fast (e.g., comparable) response times. These ratings highlight the potential positive use of haptics in providing warning feedback for drivers and the future acceptance of the system. These research efforts outline the potential benefits of using haptic warnings as an alternative countermeasure technique.

Additional methods of presenting haptic information that focus on how drivers interpret information may enhance the added benefits of haptic warnings. For instance, Ho, Tan, and Spence (2005) showed participants a series of driving videos where critical events were signaled by matched (spatially) and mis-matched vibrotactile stimulation from a belt placed around a participant's waist. Matched events included vibrotactile cues from the front of the belt corresponding to the participant vehicle rapidly approaching a vehicle ahead. A vibrotactile cue was also given on the back of the belt when a vehicle from behind was rapidly approaching. Miss-matched cues were presented opposite to matched cues. When matched and mismatched cues were compared participants had faster response times (M = 41ms) and responded with increased accuracy or made fewer errors when cued in the appropriate direction. Furthermore, when the cued data was compared to a no-cue condition, participants responded to a greater number of critical events faster suggesting a vibrotactile cue is better than no cue at all. In this instance, pairing spatial feedback to a warning system provided drivers with an enhanced direction cue that conveyed meaning (i.e., direction) and in turn directed attention through a different an alternative sensory modality (e.g., haptics).

The utility of providing directional information that does not tax primary driving visual resources is a desired alternative when providing warning information. For example, Scott and Gray (2008) found similar results when examining visual, auditory, and haptic warnings for rear end collision scenarios in a driving simulator. Response times were faster for the countermeasure condition compared to the no-countermeasure condition. Specifically, the haptic warning, induced by tactors attached to a belt and placed around a participants' front waist area, outperformed the visual countermeasures. Comparisons between the haptic and auditory warning had no significant differences and produced similar response times (M = 0.332 s and M = 0.338 s, respectively), but were still faster than the control condition (M = 0.471 s).

Overall, the previous haptic research shows the advantages of haptic warnings in facilitating appropriate and speeded responses when used as a countermeasure. Moreover, providing spatial or directional information through strategically placed warning hardware enhancing the potential safety benefit of warning these novel haptic warning devices. Collectively, these results suggest that haptics are a viable method for notifying drivers of critical events such as lane departures but, based on the paucity of systems currently in the automotive market, they are an underutilized resource.

4.2.2 Haptics and ROR Events

Addressing ROR crashes through the use of haptic countermeasures has received some interest in previous research. Kozak et al. (2006) evaluated lane departures using in-vehicle countermeasures for drowsy drivers in a driving simulator. Four specific single and paired countermeasures were tested that included: steering wheel torque, steering wheel torque with rumble strip sound, steering wheel vibration and torque, and finally steering wheel torque with a Head Up Display (HUD). The steering wheel torque was designed to provide directional indication to drivers (i.e., back to lane center) with the remaining warning types using additive cues (i.e., auditory, visual, and vibrations). Participants drove a two lane roadway and experienced controlled lane departures where the simulated vehicle was "pushed" either to the left or right off of the roadway. Each of the countermeasures outperformed the no warning condition when measuring steering reaction time. However, when examining the steering wheel vibration and torque pair they provided the fastest responses and had the highest acceptance rate compared to the other warnings. The combined haptic warnings were thought to provide notification to drivers about which direction to go to safely recover and also alert the drowsy drivers through the vibrations. The results suggest the potential benefits of using multiple haptic warnings to convey appropriate and safe driver responses as well as capitalizing on information the driver of the event. How these compare with alternative haptic warning techniques beyond the steering wheel area was not explored. Using additional or alternative haptic methods may provide a method for drivers to understand and integrate information from the warning system faster.

There have been some efforts to utilize the steering wheel and other driver centered components to provide warning information. Suzuki and Jansson (2003) compared monaural tones, stereo tones, a vibrating steering wheel, and a steering wheel torque warning lane departure countermeasure. Participants drove on straight roads during which they engaged in a secondary task. Timing for the lane departures coincided with participants' engagement in a secondary task. While a large amount of variability occurred between participants, when participants were not primed as to the meaning of the warning the steering wheel vibration reduced steering reaction time and aided in the a speeded recovery of the vehicle. Conversely, when participants were told the meaning of the warning the auditory warnings resulted in the fastest reaction times. Interestingly, a conflicting effect was found for the steering wheel torque feedback for both conditions. When the steering wheel torque was activated based on a warning condition, some participants steered in the opposite direction to the torque cue. These responses extended the lane departure and made the utility of the torque warning questionable. However, incorrect responses may have been due to the methodological set-up for the torque warning. The warning gave participants sharp jerks on the steering wheel which the authors suggest were interpreted as a wind gust rather than a warning. However, the counteraction by participants outlines the possible strength of providing a salient cue and action for participants to reacting to a force more so than a visual alert or auditory tone (Navarro, Mars, and Hoc, 2007).

The torque warning methods have received additional attention based on the potential for a warning to provide directional information and at the same time prime a directional response for drivers. Navarro, Mars, and Hoc (2007) assessed a lateral control support system in a driving simulator that warned drivers of a lane departure. The warning methods included: auditory, vibrations, a combination of auditory and the haptic feedback, and a technique called motor

priming. Motor priming (MP), a method similar to what Suzuki and Jansson (2003) employed, was described as a "directional stimulation of the hands through an asymmetric vibration of the wheel" (p. 951). The intent of MP was to initiate a response at the human motor control level in an effort to maximize response time to lane departure warnings. These techniques were compared to a baseline condition where drivers did not experience a warning prior to a critical lane departure event. Participants drove straight and curved sections of roadway and experienced visual occlusions prior to the initiation of the lane departure warning. All of the warning methods reduced the lane excursion duration compared to the baseline condition. MP warning methods showed faster response times to the other warning modalities. However, while these responses were objectively faster, there was no comparison to previous methods or combination of methods on a subjective basis. Moreover, an effective countermeasure requires both quick responses and intuitive understanding by participants that was not captured in the research.

Additional work by Navarro, Mars, Forzy, El-Jaafari, and Hoc (2010) using a similar research method showed similar benefits to the previous study, however the research included subjective rankings as part of the assessment. Again, MP and the combination of auditory and motor priming (AMP) provided objectively faster responses than alternative methods. However, when participants assessed the warnings subjectively the MP and AMP were last in the ranking system. Participants further outlined that the MP warning "felt" like an interference on the steering of the vehicle which in turn lowered the potential trust in the system. While MP provides faster response times compared to other warning methods, it is clear from these results that there is a need to account for the negative subjective assessments by participants. Combining warnings in a sequential format may provide enough information to drivers to expect additional information and potentially lessen the distrust in the system.

The previous research efforts provide the foundation to the current pilot research study. To begin, the MP warning techniques provide fast reaction times based on human reactionary responses and bypassing, to some extent, other cognitive processes utilized by visual and auditory speech methods. However, while faster response times are appealing from a safety standpoint they are of little value if participants negatively perceive the countermeasure. The consequences of misunderstanding MP can range from disliking the system, distrust of the system, or potentially exacerbating the lane departure event duration thus increasing crash risk. However, there appears to be an opportunity to use the benefits of the speeded MP responses and combine positive feedback from a subjective perspective using reduced intensities and additional haptic warnings in combination. Finally, investigating the combination of haptic warnings prior to employing a final motor prime as a potential last resort was a goal of the pilot study.

To begin, it was necessary to identify how participants responded to different haptic warning methods in isolation. The research effort wanted to explore and corroborate previous efforts by comparing haptic warnings. Participant groups were assigned to different experimental conditions. The participants in the first group compared different haptic warnings from the seat pan, seat back, and steering wheel torque (MP). The feedback levels were similar to those of previous reports in an effort to replicate previous findings and provide a foundation for additional experiments. The hypotheses were as follows:

- Motor priming (i.e., torque feedback) will result in faster response times to ROR events than alternative haptic warnings, similar to previous findings (Navarro et al., 2010; Navarro, Mars, and Hoc, 2007).
- Age groups selected for this research effort do not differentiate substantially from each other, therefore age effects are not expected to differ on any warning type.
- In-vehicle Secondary task performance will be impacted by ROR events such that those that receive a warning will have reduced performance scores.

The second group focused on the presentation of warnings. Previous research noted that response to the torque (i.e., motor prime) was negative, however the onset of the countermeasure was abrupt and as a "last resort" which may have contributed to negative feedback and distrust (Navarro, Mars, Forzy, El-Jaafari, and Hoc, 2010). There are two opportunities to improve acceptance of the torque countermeasure, the first is to reduce the intensity of the warning itself. The second is to provide a warning prior to the torque in an effort to prime drivers and rely on the torque warning as a "last resort" countermeasure. In order to investigate these elements the second group considered these hypotheses:

- The sequential presentation of two haptic warnings at a lower intensity combination of two warning types (seat pan+torque and seat back+torque) will provide faster responses than torque alone.
- The intensity of the warning contributes to the reduced acceptance of the warning, but warnings presented sequentially and at lower intensities will have higher subjective acceptance ratings.

The third group investigated the sequentical presentation of haptic warnings. Again, it was hypothesized that the addition of a countermeasure at a lower intensity would provide drivers with sufficient notice about the impending lane departure and also increase their acceptance of the warning types. Similar to Group 2 the following hypotheses were generated:

- The sequential presentation of two haptic warnings at a lower intensity combination of two warning types (seat back+ seat pan + torque and seat pan + seat back + torque) will provide faster responses than reduced intensity torque alone.
- The intensity of the warning contributes to the reduced acceptance of the warning, but warnings presented sequentially and at lower intensities will have higher subjective acceptance ratings.

A final hypothesis investigated the effect of the torque intensities (e.g., the force of the feedback) across the groups. Three torque intensities were tested across groups and included: critical, medium, and mild. The following hypotheses were generated:

- There critical force feedback from Group 1 will have faster response times compared to the other torque levels (group 2 or group 3).
- Participants will favor the lowest intensity of torque based on subjective feedback of from each group.

The following section describes the method employed to test each of these groups and related hypotheses.

4.3 Methods

4.3.1 Participants

Forty-six adults participated in the current study. Participants were divided into two age groups consisting of younger participants who were between 21-32 years of age (12 females, 12 males, mean age 26.4, *SD* = 4.1 years) and middle-age participants who were between 33-45 years of age (5 females, 17 males, mean age 38.5, *SD* = 4.2 years). The younger and middle-age participants had an average of 10.9 and 18.1 years of driving experience, respectively. All participants had a valid driver's license, had normal or corrected-to-normal vision (i.e., acuity of 20/40 or better) and had no self-reported history of any physical or cognitive limitations that may have negatively biased the conduct and results of the study. Each testing session lasted approximately two hours and participants were remunerated $20/hr for their participation.

4.3.2 Materials and Apparatus

4.3.2.1 HumanFIRST Portable Driving Environment Simulator

The pilot research effort was conducted in the HumanFIRST Portable Driving Environment Simulator (see Figure 3) that was manufactured by Realtime Technologies Incorporated. The driving environment simulator consisted of a driver's seat, vehicle controls (acceleration, steering, and brake), and vehicle gauges on a custom-fabricated chassis. Three 32-inch high-definition displays provided an 88.2 and 18.4 degree total forward field of view horizontally and vertically, respectfully. Rear-view mirror displays were inset on the forward display. The dashboard was presented on an LCD panel in a normal dashboard location. An eight-inch touch screen LCD display was located to the right of the driver and approximately 25 degrees down from the participant's horizontal line of sight (i.e., center stack HVAC area) and was used to display the secondary task. The position was selected because it required a head movement from participants to focus on the screen and engage in the secondary task thus emulating the physical and perceptual activities of normally occurring distraction tasks.

The portable simulator was outfitted with haptic feedback mechanisms. These mechanisms included tactic motors in the outboard sides of the seat pan and seat back embedded into the foam. The motors provided predetermined vibration frequencies when an ROR event occurred depending on the conditions of the experiment. A torque motor connected to the steering shaft controlled the force provided to participants by the steering wheel to emulate normal steering wheel forces and to present the haptic forces associated with the ROR countermeasures. See section 4.3.2.5 for a description of the vibration frequencies and steering wheel forces for each experimental condition.

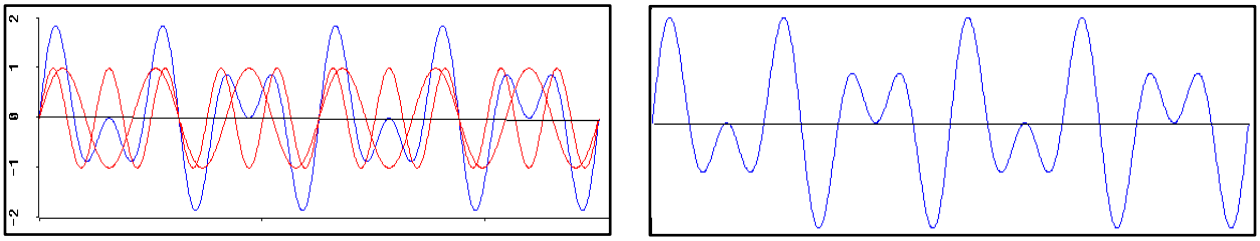
Figure 3: HumanFIRST portable driving environment simulator set up.

4.3.2.2 Simulated Driving Route

Previous research indicated that ROR crashes occurred markedly more frequently on rural versus urban roadways. Given this finding Minnesota County Road 8 and Minnesota Highway 13 were selected for use in this study because they are located in rural areas and each contained characteristics of "typical" Minnesota rural roadways that included straight segments, paved shoulders, etc. Each of the two roadways was approximately 6 miles in length (~9.6 km). Participants drove in both directions on each roadway thus creating four driving routes for the study. Ambient traffic levels of five cars/minute/mile were added to each route but were programmed so that they were not near the participant's vehicle during an ROR event.

4.3.2.3 Secondary Task

An in-vehicle secondary task was presented to participants so that driver attention could be diverted away from the roadway. It was necessary to divert attention so that drivers could not see a lane departure event developing but instead utilize the countermeasures being tested. The in-vehicle secondary task was designed to require cognitive, perceptual, and manual resources similar to normally occurring in-vehicle secondary tasks (e.g., infotainment or navigation device) but also to allow greater experimental control to eliminate potential biases that might be associated with the use of normally occurring tasks. A manual waveform tracking task was employed to achieve this. This tracking task was displayed on the touch screen positioned in the HVAC location. The task began with an auditory prompt, cuing the participant to begin. A complex waveform scrolled across the screen. The waveform was a sum of three sine waves (see Figure 4).



A **B**

Figure 4: Images depicting (A) the sum of 300 Hz and 500 Hz sine waves creating (B) one complex wave (Russell, 1997).

The waveform in its entirety (e.g. the blue waveform shown in Figure 5) was not displayed but instead a single "window" or moment of the waveform was displayed as a black dot (1.7 cm diameter) that moved with the current position of the standing waveform in an aperture window 3 cm wide by 18 cm tall (see Figure 5).

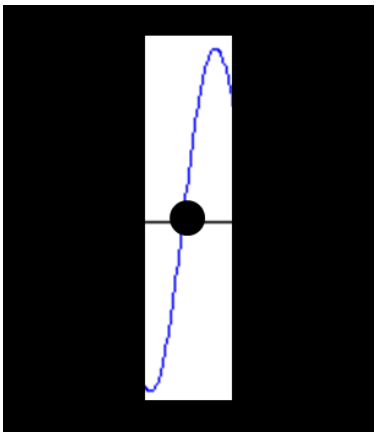


Figure 5: One instance of the waveform and corresponding black moving dot (blue waveform was shown as demonstration only, however, it was not visible to participants).

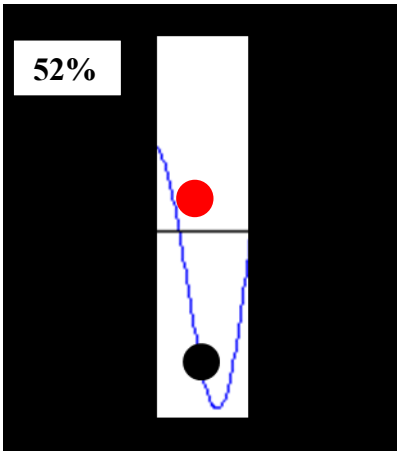


Figure 6: Waveform image with corresponding participant tracking dot (red). Blue line was not visible to participants.

The participant moved a red tracking dot (diameter of 1.7 cm) vertically with their right index finger and were instructed to attempt to cover the black dot with the red dot at all times (see Figure 6). The vertical distance between the red and black dot in millimeters measured participants' performance. The total distance possible was approximately 180 mm. Performance was measured at a sample frequency of 120 Hz and participants were given real-time feedback about their performance by a percentage denoting the running average of their success presented at the top right side of the screen. The percentage of success was calculated by their accuracy in keeping with the prescribed dot (e.g. 0% depicting the red dot was positioned the total distance possible away from the black dot and 100% depicting a perfect pairing of the red dot on top of the black dot).

4.3.2.4 Run-Off-Road Events

To initiate an ROR event the participant's vehicle encountered a gradual-to-severe wind gust spanning 4 seconds. The peak gust resembled a crosswind of 55 mph (~25 m/s) applying equal force to the entire vehicle such that the trajectory of the vehicle was pushed either left or right out or the lane of travel. The "simulated" force values followed a normal distribution over the 4 seconds. While these values do 'mimic' wind forces that may be experienced in the real-world, the exact comparative values between the force required to achieve the ROR and what may be experienced in the real world obtained face validity rather than external validity.

4.3.2.5 Countermeasure Types

The intent of the ROR countermeasures employed here was to provide information to drivers that could be used to support driver decision-making and subsequently improve the appropriateness of behavioral responses and improve perceptions of usefulness. In addition, the countermeasures were chosen because they provided information via tactile and haptic modalities that represent alternative and significantly underutilized sensory modalities when compared to visual and auditory warning modalities. Two countermeasure conditions used tactile feedback provided through the driver's seat while the third used steering wheel force feedback haptic information to convey ROR information. The countermeasures were as follows:

- Seat Pan: The tactile seat pan ROR countermeasure consisted of a vibration that occurred in either the left or right side of the seat pan depending on the direction of the ROR event. The vibration frequency was 30Hz or less (depending on condition) and felt similar to a vibrating cell phone by participants. Vibration frequencies were the least in the mild ROR events and the highest in the critical ROR events. It was expected that vibrations in each side the seat pan would indicate to drivers the direction of an ROR event while the vibration frequency would indicate the severity of an ROR event. Different levels of force were used depending on the group that was being tested. This countermeasure was chosen to provide a subtle indication of lane departure and also to be utilized as a primer for group 2 and 3 experiments.

- Seat Back: The tactile seat back ROR countermeasure consisted of a vibration that occurred in either the left or right side of the seat back depending on the direction of the event. The operational characteristics and rational for the ROR operation was identical to the seat pan ROR countermeasure. This countermeasure was chosen to provide a subtle indication of lane departure and also to be utilized as a primer for group 2 and 3 experiments.

- Torque: The haptic torque feedback provided to participants through the steering wheel was produced through a torque motor connected to the driving environment simulator steering wheel shaft. When activated during an ROR event, the torque motor created a series of steering wheel forces such that, for example, participants felt a steering wheel force for 100ms at 4 N/m towards the road center, followed by an opposite force 0.5 N/m. This pattern repeated for one second or unless the vehicle returned to the lane earlier. It was expected that the haptic feedback would serve to "prime" participants to the direction of the necessary response. The countermeasure was chosen based on the positive findings

(e.g., fastest response times) from previous research (Navarro et al., 2010). To explore additional potential benefits the force of feedback was also manipulated.

4.3.2.6 Countermeasure Groups

Answering the primary research questions cited in the introduction of Section 4 required the use of three experimental groups that differed according to the number of ROR countermeasures presented to participants and the timing and magnitude of feedback for the countermeasures. Each of experimental groups contained four conditions: a Baseline condition in which no ROR countermeasure was presented with an ROR event and three treatment conditions, each of which pairing one or more ROR countermeasures with an ROR event. Table 7 summarizes the specific operational characteristics of the ROR countermeasures within each treatment condition in each experimental group. A summary of the experimental groups and rationale for the inclusion of the treatment conditions is presented below.

Group 1 was composed of four conditions which, when compared, examined driver behaviors in response to ROR events when unsupported (i.e., Baseline condition) and when supported by an ROR countermeasures via torque feedback (Condition 2), seat back feedback (Condition 3), or seat pan feedback (Condition 4). A comparison of driver behaviors across these conditions indicated which ROR countermeasure, when provided alone, resulted in the greatest improvements in driving performance and the highest subjective ratings. This examination was designed to test driver response and satisfaction to each haptic warning method (i.e. steering torque, seat pan, and seat back) individually, presented at full intensity. Each individual haptic warning would be presented at when drivers crossed a final threshold (195 cm from lane center). This threshold was set as an absolute threshold in which a lane departure is imminent and a more powerful countermeasure is necessary (i.e. high intensity warning). The purpose of this examination was to determine if the hypothesis is correct that any of the three countermeasures are superior to Baseline (i.e. no warning) in preventing a ROR crash and that faster response times, but poorer subjective ratings, would be found for steering torque compared to alternative haptic measures, seat pan and seat back.

Group 2 also compared driving performance in response to ROR events between a no ROR countermeasure condition (Baseline) and three treatment conditions in which ROR countermeasures were provided. The torque feedback in Group 2 differs from Group 1 in that the intensity of the warning has been partially reduced to determine if a medium intensity torque can still produce better response times compared to Baseline. This examination was also designed to determine if presenting additional haptic warnings prior to the onset of the reduced intensity torque method could improve drivers' objective and subjective responses compared to the Torque only condition. The medium torque intensity was prefaced with either a haptic seat pan or haptic seat back, each presented at a medium intensity compared to their previous intensity in Group 1 (see Table 7). The manipulation of the haptic signals in Group 2 and Group 3 both attempt to address the issue of the sudden onset of the torque signal by presenting a less intrusive signal prior to the final threshold point. Furthermore, the inclusions of the additional countermeasures were expected to offset any loss in reaction time or recovery speed due to the weakened intensity of the torque.

The structure of Group 3 was similar to Groups 1 and 2. There was a control (Baseline) condition and three treatment conditions. The examination in Group 3 further investigates the degree to which the intensity of the torque feedback can be reduced to preserve the effectiveness of the warning while improving users' subjective ratings of the system. The mild torque intensity was prefaced with both haptic seat signals in presented in counterbalanced, sequential order (seat pan then seat back or seat back then seat pan), each presented in a mild intensity compared to Group 1 (see Table 7).

A final examination in this study was designed to determine the impact of steering torque intensity reduction on drivers' objective and subjective responses across Group 1, 2, and 3. Three torque intensities tested across groups were: critical, medium, and mild. Each torque intensity was presented at the final lane threshold (i.e. 195 cm) to provide drivers with a countermeasure to prevent a ROR event or to impose a quicker recovery from the event. The purpose of this examination was to determine a reduction in signal intensity would improve drivers' subjective rating of the countermeasure while also determining the extent to which objective responses (i.e. reaction time and recovery time) is diminished by the weaker signal. This manipulation attempts to address the issue of the intrusiveness of the torque related to its strength.

Table 7: Countermeasure types and points of activation.

		Point of Activation (distance from lane center) and Feedback Type		
Group	**Condition**	**145 cm**	**170 cm**	**195 cm**
Group 1	Baseline			None
	Condition 1			Torque: 4 N/m for 100ms, 0.5 N/m for 200 ms
	Condition 2			Seat Pan: 30 Hz for 1 s
	Condition 3			Seat Back: 30 Hz for 1 s
Group 2	Baseline			None
	Condition 1			Torque: 3 N/m for 100ms, 0.5 N/m for 200 ms
	Condition 2		Seat pan: 20 Hz for 1 s	Torque: 3 N/m for 100 ms, 0.5 N/m for 200 ms.
	Condition 3		Seat Back: 20 Hz for 1 s	Torque: 3 N/m for 100 ms, 0.5 N/m for 200 ms,
Group 3	Baseline			None
	Condition 1			Torque: 2 N/m for 100ms, 0.5 N/m for 200 ms
	Condition 2	Seat pan: 10Hz for 1 s	Seat back: 10Hz for 1 s	Torque: 2 N/m for 100ms, 0.5 N/m for 200 ms
	Condition 3	Seat back: 10Hz for 1 s	Seat pan: 10Hz for 1 s	Torque: 2 N/m for 100ms, 0.5 N/m for 200 ms

4.4 Procedure

4.4.1 Introduction

When participants arrived at the University of Minnesota for the experiment, they were presented with, read, and signed an informed consent form. After completing the consent form, participants were asked to complete a driving history questionnaire and completed a visual acuity test to ensure normal or corrected to normal (20/40) vision.

4.4.2 Practice Trials

Each participant was randomly assigned to a countermeasure condition (Condition 1, 2, or 3) and were then provided with practice trials to acclimate them to the driving simulator, secondary tasks, and ROR countermeasures. All participants were given instructions indicating how to complete the secondary tracking task. Participants then performed a practice trial in the driving environment simulator in which they drove a portion of the practice route and then set the cruise control to 55 mph. Participants were then prompted with an auditory beep to engage in the secondary tracking task. No ROR event was presented so that participants could become proficient in the in-vehicle secondary task thus reducing the possibility of a bias due to participants learning the in-vehicle secondary task during experimental drives. Participants continued to drive and were presented with four ROR events caused by crosswinds while they performed in-vehicle secondary tasks. No detail was provided to them beyond being instructed that they would at times experience a “warning” when they departed the road. Participants did not experience a ROR countermeasure during the first ROR event. Participants did experience the torque countermeasure in the second ROR event. Participants assigned to Condition 1 experienced the seat pan and seat back ROR countermeasures in ROR events 3 and 4, respectively. Participants assigned to Condition 2 experienced the seat pan and torque and then the seat back and torque ROR countermeasures in ROR events 3 and 4, respectively. Finally, participants in Condition 3 experienced the seat pan, seat back and torque and then the seat back, seat pan, and then torque ROR countermeasures in ROR events 3 and 4, respectively.

4.4.2.1 Test Trials

Participants drove through four driving routes with each lasting 11 to 15 minutes depending on speed variations by participants. Only one Condition (1, 2, 3, 4) was experienced throughout each drive (i.e., block presentation of Conditions). The order of block presentation was randomized for each participant.

During each route, participants were asked to drive as they normally would and were asked to engage the cruise control upon reaching 55 mph (the speed limit for the roadway). Activating the cruise control served to standardize across all participants the speed at which participants traveled when experiencing a ROR event. During each route, participants were prompted to complete up to 10 in-vehicle secondary task tracing activities with two being randomly selected to be paired with a crosswind causing a right or left ROR event. The ROR event only occurred on straight sections of roadways. Oncoming traffic was presented at a rate of 1 car every 8 seconds; however, cars were not located at or near the ROR critical event locations.

In the case of an unplanned ROR event (i.e. the participant leaves the road when a wind gust had not been presented) no countermeasure was presented. This was implemented so that each participant received the same number of ROR events and so that those who had more difficulty staying in their lane in non-crosswind situations were not exposed to a disproportionate number of ROR countermeasures.

Following each driving route participants rated the ROR countermeasure they just experienced using the System Usability Scale (SUS) (Appendix B). At the conclusion of the final driving route, participants completed a short-post drive questionnaire (Appendix C) to gauge their overall impressions of the ROR countermeasures.

4.5 Experimental Design

4.5.1 Dependent Variables

The dependent variables included:

- *Response time*. Response time was calculated as the difference between the point where the first countermeasure was initiated to the peak of the vehicle trajectory or deviation. Trajectory of the vehicle was calculated as the extent of the deviation out of the lane boundary. The peak was determined to occur when the maximum extent of the ROR occurred and the vehicle did not deviate further. Braking was not considered to be the primary response compared to steering back onto the roadway. Failing to make a response or steering in the wrong direction was discarded from the data set. This measure was included to provide an indication of the amount of time required to correct an ROR event based on the countermeasure type presented. Fast response was deemed to be better than slow response times.
- *Re-entry Time (total time to re-enter the lane).* Lane re-entry time was calculated as the difference between the points where the far right front tire departed the edge of the lane to the point where the edge of the right front tire crossed the same point back into the lane. Low scores indicated a short duration lane departure which was preferred.
- *In-Vehicle Secondary Task (task accuracy).* In-vehicle secondary task scores consisted of the mean accuracy of the task during the ROR events. This was included as a measure of task shedding or task engagement during an ROR event. Low scores indicated poor task accuracy.
- *System Usability Scores (SUS)*. The SUS provided a user rated measure of a participant's perception of how well a countermeasure performed. Participants rated each countermeasure at the conclusion of each drive using a Likert scale. Scores were converted and combined into one score that ranged from 0 to 100. Low scores indicated poor perceptions of usability. A SUS score above a 68 is considered above average while a score below 68 was considered below average. The SUS scoring questions are presented in Appendix B.

4.5.2 Statistical Design

Data for each of the three Groups were analyzed separately using the following approaches. Response time was only analyzed using the countermeasures presented and was not analyzed for

the baseline condition. The rationale for excluding the baseline for this analyses was based on the fact that precision of when to compute response time was not consistent. Initiation times for countermeasures were evident and sometimes varied based on lane position of the participant vehicle. Therefore, for the response time analysis, only a 2 x 3 mixed model ANOVA was used with Age (Younger and Middle Age) as a between subject factor and Condition (Condition 2, Condition 3, Condition 4) as a within subjects factors. Re-entry time and in-vehicle secondary task data were each analyzed in a 2 x 4 mixed model ANOVA with Age (Younger and Middle Age) as a between subjects factor and Condition (Condition 1, Condition 2, Condition 3, Condition 4) as a within subjects factor. Post hoc analyses were conducted using a follow up pairwise t-test comparisons using a bonferroni correction to account for the number of comparisons. SUS scores were analyzed using a t-test comparisons between each Condition. An alpha level of 0.05 for used for all analysis.

4.6 Results

Only significant or marginally significant results of the analyses for each Group are presented.

4.6.1 Group 1

4.6.1.1 Response Time

Results indicated a marginally significant effect for Age ($F(1, 41) = 3.99$, $p = .052$) with younger drivers response times being faster $M = 0.92$s ($SE = 0.07$s) than the middle aged drivers $M = 1.10$s ($SE = 0.06$).

4.6.1.2 Re-Entry Time

Results indicated a significant main effect ($F(1, 62) = 8.81$, $p=0.04$) for age with the younger drivers exhibiting significantly faster re-entry times ($M = 2.75$s, $SE = 0.19$s) compared to the middle age drivers ($M = 3.56$s, $SE = 0.19$s).

4.6.2 Group 3

4.6.2.1 Response Time

Results of the response time analysis indicated a significant main effect for Condition ($F(2, 96) = 4.05$, $p = 0.020$). Post hoc analyses indicated that Condition 2 (torque) was associated with a significantly faster response time ($M = 1.02$s, $SE = 0.09$s) when compared to Condition 4 (seat pan, seat back, torque) ($M = 1.28$s, $SE = 0.07$s). The differences in response time for this main effect are shown in Figure 7. It should be noted that the ROR countermeasure initiation times occurred sooner for Condition 4 compared to Condition 2 or the singular torque setting. These results suggest that the additional priming via the seat haptics did not promote faster response times and may have added to the delayed response times.

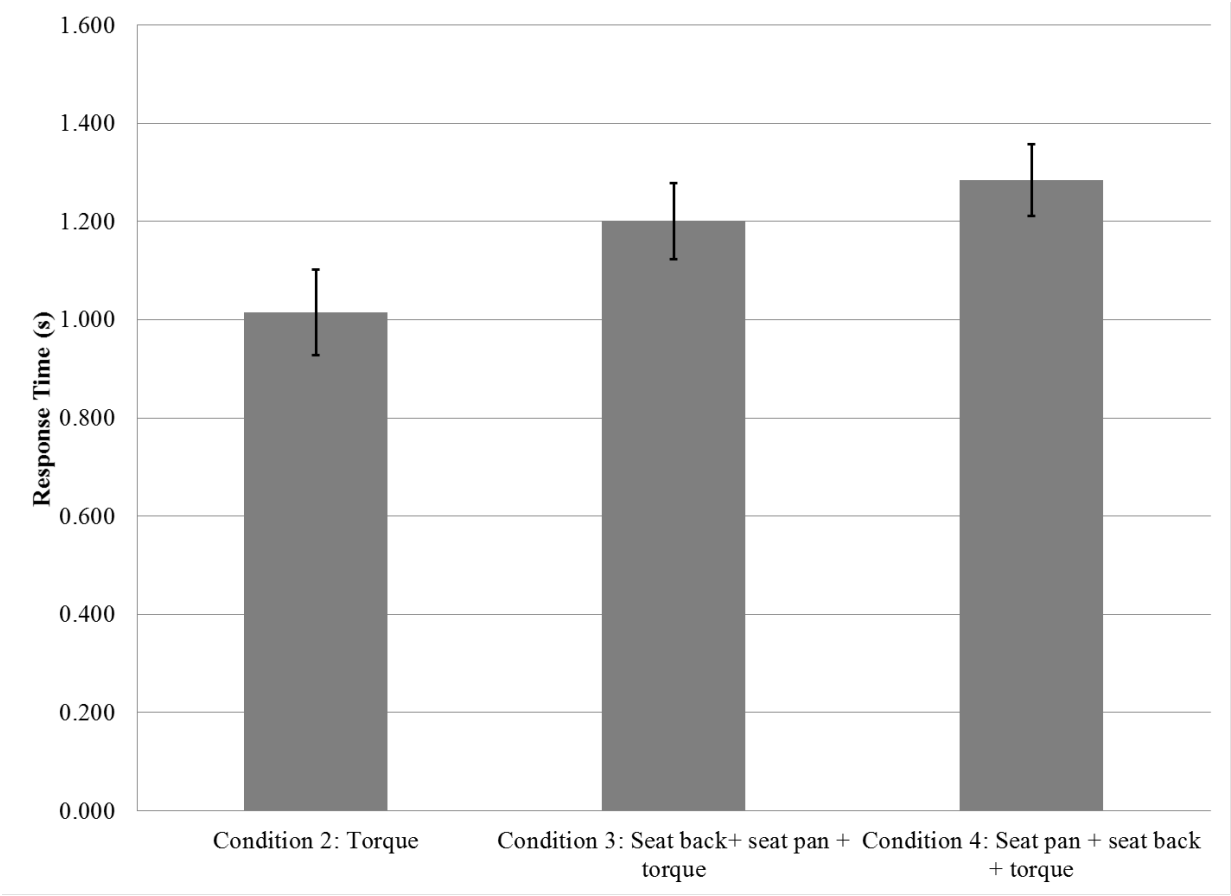


Figure 7: Response times to single and multiple countermeasures.

4.6.3 Countermeasure Intensity

Recall a final examination in the study was designed to determine the impact of steering torque intensity reduction on drivers' objective and subjective responses across Group 1, 2, and 3. Results indicated a marginal difference between groups for the re-entry time ($F(2, 179) = 2.55$, $p = 0.081$). Participants had shorter re-entry times in Group 1 torque condition (M = 3.17s, SE = 0.22) compared to Group 3 torque (M = 4.09s, SE = 0.36s). Despite the additional sequential warnings and the reduced torque warning, the single torque presentation assisted drivers faster in re-entering the lane after the departure.

4.6.4 System Usability Scores (SUS)

4.6.4.1 Group 3

Results indicated a significant difference ($t(15) = -3.21$, $p = 0.06$) between Condition 2 (torque) (M = 61.1, SE = 4.42) and Condition 4 (seat pan, seatback, torque) (M = 74.0, SE = 3.87). This is an important result since the average SUS score for Condition 2 (torque) is considered below average and the SUS score for Condition 4 is considered above average. There were no differences between Condition 2 (torque) (M = 61.1, SE = 4.42) and Condition 3 (seat back, seat

pan, torque) (M = 71.1, SE = 4.02). These results suggest that multiple ROR countermeasures may be perceived as being satisfactory and meaningful and, as a result, may be preferred to single ROR countermeasure.

4.7 Countermeasure Evaluation Discussion

The aims of the pilot study countermeasure evaluation were to investigate the efficacy of three different haptic countermeasures to prevent ROR crashes, identify the torque thresholds required elicit an appropriate response to a ROR event, and to examine haptic countermeasure combinations to maximize driver performance and system usability and satisfaction. These aims were pursued through a strategic presentation of multiple versions of haptic countermeasures in a simulated rural driving environment.

4.7.1 Single Presentation Countermeasures

Based on previous research findings, torque feedback was expected to provide faster response and re-entry times compared to the other haptic countermeasures (Navarro, Mars, and Hoc, 2007). No differences were demonstrated, however, between the three haptic warning types. While the effect of the MP was expected to be most pronounced through the steering wheel feedback, our findings suggest that other haptic measures are equivalent in conveying ROR event information and illiciting an appropriate response to an impending lane departure incident. Furthermore, Suzuki and Jansson (2003) noted that almost half of the participants that were presented with the torque feedback in their study mistakenly corrected in the opposite direction causing longer lane departures. These effects were not observed in the current study nor were any differences found for re-entry duration between the warning methods.

The torque warning was expected to outperform all of the other haptic devices (e.g., see Navarro, Mars, and Hoc, 2007). However, this was not the case and as such provides some utility for the additional haptic warnings tested. In the majority of cases there were no differences and as such the other warning types performed as well as the single torque warning. However, the methodology employed for the single countermeasure presentations may not have been rigorous enough to elicit differences between groups. The equivalent responses between the warning types could be attributed to a number of reasons. The lack of differences may be a result of the driving environment by which the lane departures events were presented. The wind events which triggered the lane departures were presented in straight sections of roadway with no conflicting traffic present. The consequence of the chosen simulated environment may be that the lane departures lacked a motivating feature of curves or oncoming traffic to encourage drivers to urgently re-enter the roadway, ultimately leading to drivers “easing” back into the roadway. These findings would need to be replicated in order to verify consistency and applications of warning.

While no measurable differences were obtained between warning types, there were significant differences between the age groups. Younger drivers, overall, were marginally faster to respond to the ROR event and had significantly quicker re-entry times back to the lane center compared to their older counterparts. Although younger drivers are expected to have faster response times, this disparity is typically mitigated by the fact that middle-aged drivers have more experience and tend to respond more appropriately. In this instance, the response by younger drivers was not

only faster, but also appropriate as evidenced by the re-entry time. The age impact was only found for overall response times and did not significantly differ between the warning types, suggesting the application of specific haptic warning types were not impaired by age. Torque feedback was not favored by the younger drivers suggesting that even though all forms of haptic feedback were effective for younger drivers, but that more research on the force and type of haptic feedback is required prior to deployment to ensure the systems are accepted by users. These unexpected age effects provide valuable insight into the need to further investigate the differential impact of warning systems on even relatively close age groups.

While the intent of the secondary task was to provide a distraction prior to and during the wind induced ROR event, an additional expectation was that performance scores would decline as drivers attended to the event and shed the secondary task; however, this was not the case. The performance scores obtained appeared to have a ceiling effect (*M's* = 94-96%) for all haptic warning types. The results suggest that the secondary task may not have been complex enough and neither sufficiently visually demanding or attentionally taxing. The lack of differences, however, also suggests that the haptic countermeasures did not interfere with other visual attentional resources drivers were applying to the driving task. Again, these results were unexpected, but provide a basis for additional research in testing other secondary tasks and workload effects on ROR events.

Overall, few differences were obtained from the initial Group 1 comparisons in which single presentation of haptic warnings were given to drivers while they performed a secondary task. Subtle age differences were identified, but few confirmatory results were obtained when compared to the previous research guiding the initial aim of the research effort. The central question, however, was to assess the utility of haptic warnings for ROR events and the results appear to support their efficacy compared to control conditions.

4.7.2 Sequential Haptic Countermeasures

The utility of the sequential warnings, or paired haptic warning, was to notify the driver earlier that they were approaching a lane departure and to prime drivers prior to the initiation of the final torque signal to allow them to prepare to take action. The results from the two-step sequential warning (i.e., group 2), however, failed to demonstrate this effect. There were no observed differences between the single torque warning and either of the paired, sequential warnings for this group. While unexpected, the results suggest two things-- first, the earlier warning did not provide a faster response time or re-entry time for participants compared to the later, single warning. Drivers may have refrained from reacting while attempting to understand the meaning of the warning itself. Moreover, the intent of the initial warning was to prompt the driver that a lane departure was occurring and to expect additional follow up information regarding this departure; however, there was limited time between the initial signal and the next warning. The warning timing, when sequentially paired, will need further examination in order to identify these potential shortcomings.

Secondly, the intensity or force of all warnings were reduced in this grouping. While it was expected that an earlier notification would prompt a faster response, it was possible that the force of the warning did not adequately convey the urgency of the lane departure. Participants were provided minimal information about the warnings in an attempt to measure the intuitiveness of

the warnings to naïve users. The sequential warnings for this group may have been more effective had a more extensive and detailed explanation been provided to participants prior to their exposure. The absence of differences also shows that the single warning presentation provided sufficient information despite being initiated at a later time than the sequential warnings. Drivers, when notified later, were further into the lane departure event and may have utilized the visual road environment to inform the speed and direction of their response. An examination of these notification differences will provide insight into the utility of sequential warnings.

Finally, when the different warning types were compared using the subjective SUS scores there were no differences between the warning types. It was hypothesized that the sequential sequence of the warnings, i.e. priming drivers prior to the final torque warning, would have higher subjective ratings since the warning provided additional information prior to the final torque warning in the sequence. This was not the case given the results suggest that the lower intensity single torque warning was equally effective and received comparable subjective scores to the sequential warning pair. The lack of differences here suggests that the force used for the single torque warning was sufficient in providing information and was not considered obtrusive as found in previous research (Mars, Forzy, El-Jaafari, and Hoc, 2010; Suzuki & Jansson, 2003). These results speak to the importance of the force used in the feedback information, suggesting the level used for this group were appropriate in conveying the meaning and response requirements.

4.7.3 Sequentially Presented Countermeasures

The third group explored the effectiveness of presenting three sequential warnings compared to the single torque in an effort to examine the impact of ample information being provided to drivers. The intent, similar Group 2, was to provide drivers a set of initial, low intensity, warnings prior to invoking the final torque feedback at the end of the series. Researchers anticipated that priming drivers prior to the final warning would result in faster response/re-entry times and higher subjective ratings. The results from the response times and re-entry times, however, were opposite to expectations. The single torque warning presentation had faster response times than the third sequential warning (i.e. seat pan, seat back, then torque) which primed participants earlier. The sequential warnings may have imposed an additional attentional burden to drivers which could have slowed comprehension and response times. Interestingly, the second sequential warning (i.e., seat back, seat pan, then torque) had comparable response times to the single torque warning presentation. Furthermore, there were no differences between the two sequential warning presentations. These disparate results show that the presentations of the warnings, in a sequential arrangement, are interpreted in a different manner. While the sequences of the warnings were manipulated, the information being conveyed was not. It appears that initiating a warning via the seat back, then providing a warning through the seat pan prior to the final torque warning may aid in conveying critical information. Why these subtle differences occurred requires additional research into how pairings of specific haptic systems may inhibit or enhance responses.

Finally, the subjective ratings by participants were significantly different depending on the warning type. Specifically, participants rated the single torque warning lower than the third sequential warning (i.e. seat pan, seat back, then torque). The subjective differences provide two

points of discussion. First, torque warning was at a reduced intensity compared to the first two groups. The low intensity may have served as an annoyance rather than as an effective countermeasure. The lower intensity primed sequence of warnings may have helped to convey the warning information in a smoother transition across warning types. The other sequential warning (i.e., seat back, seat pan, torque) also had a higher average subjective score (i.e., 10% higher) compared to the single torque presentation; however, this difference was not significant. The timing of the warning may have also contributed to the single torque's lower subjective scores. The torque was placed at a "critical" decision point where participants were well into a lane departure event and the vehicle had substantially deviated from the roadway. This presentation may have been perceived as "too late" as an appropriate preventative warning. The alternative sequential warnings fired sooner at points still within the lane boundary and may have been seen as more reliable than the single torque warning. Refining how the warnings were presented and how they were interpreted by drivers will provide further insight in the future.

4.7.4 Torque Countermeasure Intensity

The final set of questions investigated if the intensity of the torque (alone) impacted how drivers responded to and rated the haptic countermeasures. Group 1 participants had marginally faster re-entry times from a lane departure event compared to the group three. The results present an interesting effect that initiated the final set of questions. The focus of the MP warning was to bypass slow attentional processes and induce a reactionary motor response, resulting in faster response times. Subjective ratings of the force used were directly related to the intensity, however, such that the highest force provided the fastest response times, but the lower subjective ratings. Similar to previous research (see Mars, Forzy, El-Jaafari, and Hoc, 2010) it appears the sequential warnings and lower force warnings presented in this study did not accomplish the desired balance of fast response times *and* high subjective ratings. Overall, for safety reasons high intensity single torque presentations were favored because they resulted in the fastest response times.

4.7.5 Limitations

The current project was an initial research effort to integrate multiple countermeasure types and feedback alerts for ROR events. The research also reviewed the intensity of the countermeasure type and how such manipulations may impact the responses by participants. The results of the research effort did not find consistent and definitive answers to some of these questions. The results may have been impacted by the presentation styles of the ROR countermeasures, the ROR events themselves, and secondary task interactions.

The research effort was conducted on a driving simulator that provided a high level of fidelity, but also did not provide significant real-world consequences if a participant were to depart the lane in an actual vehicle in a true ROR situation. The lack of actual consequences may have impacted their interpretation of countermeasure types and, consequently, their responses to them. Furthermore, in order to initiate a ROR, the researchers had to program a significant "wind gust" to push the participants' simulated vehicle out of the roadway. The types of "wind gusts" are likely encountered infrequently by drivers in the real-world and thus the number of these events presented over a short hour period likely primed the individuals to expect and create anticipatory responses to the visual road environment rather than the warnings themselves.

There are several recommendations for future research based on the experiences gained in this study. To begin, the researchers used a secondary task that provided some task difficulty for participants but perhaps lacked validity for actual in-vehicle tasks. Future research could investigate different levels of secondary task difficulty and impact on ROR events. Different types of secondary tasks (e.g., visual/auditory) likely influence the extent of RORs and should be investigated in future research. In addition, multiple countermeasures will be a mainstay of future vehicles and how these multiple countermeasures are integrated was of great importance. Multiple countermeasure methods, subtle to intense, and ordering of alerts will impact how drivers and when they respond to different critical events and should be thoughtfully investigated in the future.

Chapter 5. General Discussion and Conclusions

The overall results from the pilot study research effort were mixed. Previous work using MP has focused on its utility to bypass attentional resources and initiate a speeded reactionary motor response (Deroo, Mars, and Hoc, 2013; Navarro, Mars, Forzy, El-Jaafari, and Hoc, 2010; Navarro, Mars, and Hoc, 2007). Additionally, providing the warning through the steering wheel via a MP method conveys directional information for participants, specifically pertaining to lane keeping or lane departure situations. The results from the current effort support previous evidence of speeded responses using the MP methodology. Furthermore, the research effort showed that increased intensities of the warning are conducive to faster responses similar to other findings (Deroo, Mars, and Hoc, 2013; Beruscha, Augsburg, Manstetten, 2011). The results suggested that lower forces may be misconstrued or ignored altogether (Kozak et. al., 2006). The use of alternative haptics (i.e seat pan or seat back) as lane departure warnings was also comparable to the torque (MP) only conditions for the first group of participants. The use of multiple haptics warnings in sequence, however, provided little to no additional support for drivers encountering lane departures. These multiple presentations of warnings indicated a potential for overloading a driver with warning information and consequently inhibiting an appropriate response or delaying the response similar to results found for other in-vehicle systems (Lee, McGehee, Brown, and Marshall, 2006). The results also suggest that some haptics may be better matched for different warnings types, similar to the use of auditory or visual warnings in specific situations. While additional research is required, the use of MP in critical steering situations, does lend support to the notion of applying directed warning feedback to specific vehicle areas (Navarro, Mars, and Hoc, 2007).

The overall research effort suggests a need to further investigate an overlooked and critical area of driving safety. Recall that in Minnesota and nationwide, ROR crashes account for over 50% of all vehicle crashes (Minnesota Crash Facts 2012; FHWA Roadway Departure Strategic Plan, 2013). Furthermore, ROR crashes are particularly problematic in rural areas where over 80% of crashes were attributed to ROR events (Neumann et al., 2003). While efforts have been initiated (e.g., Minnesota) to investigate and mitigate some of these issues, these statistics have remained relatively stable over the last 8 years -- despite the introduction of infrastructure and some initial in-vehicle support systems. Clearly, additional research is needed to further close the gaps in the literature obtained when constructing the taxonomy framework. The taxonomy itself requires additional work to investigate vehicle-to-infrastructure, vehicle-to-vehicle, and infrastructure-to-vehicle solutions. These are likely moderated by external infrastructure connected systems in addition to complex in-vehicle systems.

Also recall that driver behavior was identified as one of the leading contributors to ROR crashes, yet understanding how to mitigate driver behavior crashes and how to integrate multiple sensory warnings has received minimal attention. While work in lane departure and lane keeping assist areas have been pursued by automotive manufacturers, additional work based on how information is conveyed and how drivers interpret and react to ROR information requires further investigation beyond the current research effort. Drivers will likely be exposed to multiple warnings with multiple meanings and assessing the consequences of these attentional demands will help drive the next generation of ROR warnings.

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Appendix A: Driving History Questionnaire

DRIVING HISTORY QUESTIONNAIRE **Participant #_____**

This questionnaire asks you to indicate some details about your driving history and related information. Please tick one box for each question.

1. Your age: _____ years

2. Your sex:

☐ Male

☐ Female

3. What is your highest educational level completed?

☐ High School / Vocational School

☐ Associates Degree

☐ Bachelor of Arts / Bachelor of Science

☐ Masters

☐ PhD

4. Are you currently taking any college level classes?

☐ Yes

☐ No

5. Please state your occupation:_____

6. Please state the **year** when you obtained your full driving license: _____

7. About how often do you drive nowadays?

☐ ======= ☐ ======= ☐ ======= ☐ ======= ☐

Never	Hardly Ever	Sometimes	Most Days	Every Day

8. Estimate roughly how many miles you personally have driven in the past year:

☐ Less than 5000 miles

☐ 5000-10,000 miles

☐ 10,000-15,000 miles

☐ 15,000-20,000 miles

☐ Over 20,000 miles

9. About how often do you drive to and from your place of work?

☐ ======= ☐ ======= ☐ ======= ☐ ======= ☐

Never	Hardly Ever	Sometimes	Most Days	Every Day

Do you drive frequently on…	Yes	No
10. Highways?	☐	☐
11. Main Roads other than Highways?	☐	☐
12. Urban Roads?	☐	☐
13. Country Roads?	☐	☐

14. During the last three years, how many minor road crashes have you been involved in where you were at fault? A minor crashes is one in which no-one required medical treatment, AND costs of damage to vehicles and property were less than $4000.

Number of minor crashes ____ (if none, write 0)

15. During the last three years, how many major road crashes have you been involved in where you were at fault? A major crashes is one in which EITHER someone required medical treatment, OR costs of damage to vehicles and property were greater than $4000, or both.

Number of major crashes ____ (if none, write 0)

16. During the last three years, have you ever been convicted for:

	Yes	No
a. Speeding	☐	☐
b. Careless or dangerous driving	☐	☐
c. Driving under the influence of alcohol/drugs	☐	☐

17. What type of vehicle do you drive most often?

☐ Motorcycle

☐ Passenger Car

☐ Pick-Up Truck

☐ Sport utility vehicle

☐ Van or Minivan

☐ Other, briefly describe: _____

Appendix B: System Usability Score

ROR Countermeasure System Questionnaire
For each of the following questions, CIRCLE one number to indicate your response.

"1" for strongly disagree, "3" for neutral- neither agree nor disagree, "5" for strongly agree.

Strongly Disagree 1	2	3	4	Strongly Agree 5
○	○	○	○	○

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

Appendix C: ROR Countermeasure Final Questionnaire

ROR Countermeasure System Final Questionnaire

For each of the following questions, please write a few sentences.

A. How did you feel about each of the different ROR countermeasures (steering wheel, seat pan, seat back, no countermeasure, etc)?

_____
_____
_____
_____
_____
_____

B. Which countermeasure did you prefer? Which countermeasures did you like the least? Why?

_____
_____
_____
_____
_____
_____

C. Do you feel that the countermeasures improved your ability to return to the lane quickly? Why or why not?

_____
_____
_____
_____
_____
_____

D. Did you understand the meaning of and required response for each countermeasure? Were the countermeasures confusing or clear?

_____
_____
_____

E. Which countermeasures do you feel were the most effective? Which countermeasures were the least effective?

F. What would you change about the countermeasures?

_____
_____
_____
_____
_____
_____

G. Would you be willing to purchase a ROR countermeasure system? Would you be willing to take a free one if it was offered to you?

_____
_____
_____
_____
_____
_____