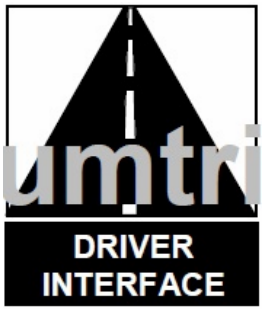
Technical Report UMTRI-2014-34 December, 2014

Crash Warning Systems: The Human Factors Literature and a Design Framework

Paul Green, Sakinah Echols, and Javier Taylor



Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UMTRI-2014-34		

4. Title and Subtitle	5. Report Date
Crash Warning Systems: The Human Factors Literature and a Design Framework	December 2014
	6. Performing Organization Code account 351518
7. Author(s) Paul Green, Sakinah Echols, and Javier Taylor	8. Performing Organization Report No. project grant N017117
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute (UMTRI) 2901 Baxter Rd, Ann Arbor, MI 48109-2150 USA	10. Work Unit no. (TRAIS)
	11. Contract or Grant No. DRDA 13-PAF05797
12. Sponsoring Agency Name and Address Hyundai-Kia America Technical Center (HATCI) Engineering Design – Packaging/Ergonomics 6800 Geddes Rd, Superior Township, MI 48198 USA	13. Type of Report and Period Covered November 2013 – December 2014
	14. Sponsoring Agency Code

15. Supplementary Notes
Attention: Claudia Escobar

16. Abstract

The report summarizes (1) the kinds of crashes that occur and for what warnings are needed (using the Najm, Smith, and Yanagisawa 37 crashes typology), (2) some of the recent and key studies of human factors aspects of motor vehicle crash warnings (SAVE-IT, IVBSS, CWIM, Jeong and Green, 2012), (3) the characteristics of good warnings (e.g. error feedback, positive guidance, consistent format), (4) human factors guidelines for motor vehicle warnings (COMSIS, Battelle), (5) human factors research on warnings for specific purposes (e.g., forward crash, lane departure, lane change/merge, backing), and (6) provides a framework for warning system design. Given the limited resources available, this report examines warning modality and content, the topic of greatest interest, not warning timing.

Key findings include the following. First, many of the studies involve the comparison of warnings that differ in modality and other characteristics. However, the compared warnings differ in many other ways and it is unclear that they have been optimized with a modality. From those studies, there is no clearly best warning for a particular purpose (e.g., forward crash). Second, except for IVBSS, the focus is on individual warnings, not on how a set of warning will function together.

17. Key Words	18. Distribution Statement
human factors, ergonomics, safety, warnings, lane-departure warning, blind-spot warning, forward-crash warning, backup warning	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classify. (of this report)	20. Security Classify. (of this page)	21. No. of pages	22. Price
(None)	(None)	78	

Form DOT F 1700 7 (8-72) **Reproduction of completed page authorized**

Paul Green, Sakinah Echols,
and Javier Taylor

University of Michigan
Transportation Research Institute
Ann Arbor, Michigan, USA

1. How often do various types of crashes occur and under what circumstances do they occur? What are the implications for warning design?
2. What are the characteristics of a good warning?
3. What are some of the major guidelines concerning crash-warning design?
4. What is some of the recent research on crash warnings?
5. What are some of the major findings with regard to specific crash warning systems (e.g., forward crash warning, lane departure warning, back up warning, lane change/blind spot warning)?
6. Based on the information gathered and expert opinion, what could be a framework for motor vehicle warnings?

1. Examine primary articles and guidelines listed in proposal
2. Examine research by first author and publications in his personal library
3. Search using Google and Google Scholar
   example terms: forward crash warning, lane departure warning, etc. sometimes with -
   —human factors, driver interface, etc.
4. Examine references in articles/reports and references citing them with focus on recent

3 Findings

Warnings should be developed considering the object or action about which the driver is unaware for each maneuver.

Consideration of Najm, Smith, and Yanagisawa (2007) 37 scenario crash typology (control loss with prior vehicle action, control loss with prior vehicle action, lead vehicle decelerating, non-collision event ~~([~~e.g., fire~~])~~ helped identify about what to warn

Common Scenarios Emerging from That Consideration

Maneuver	Warn About – Object or Action
driving straight, usually but not always expressway	objects ahead (slow, stopped, changing lanes)
driving straight	drifting from lane (or other vehicles drift)
changing lanes	other vehicles
driving straight and approaching intersection	other vehicles/objects at intersection
approaching intersection	missed stop sign or traffic signal (at intersection)
backing up	other vehicles, leaving lane, exiting parking
driving straight or turning	hidden/obstructed bike, animal, pedestrian, all especially at night
all	fires, submerged (and make exit easy)
all	vehicle failure

Damouth and Green (1997) identify the characteristics of a good warning, some of which are listed here.

#	Criteria	Primary Question
1	Understandability	Do drivers understand the message (as indicated by the understandability data and/or their comments)?
2	Desired response	Do drivers carry out the wrong action or actions at the wrong time?
3	Error feedback	Does the message tell the driver what is wrong?
4	Positive guidance	Does the message tell the driver what to do?
5	Specificity	Could the driver interpret a message in more than one way?

There are 2 Existing Sets of Motor Vehicle Warning Guidelines, COMSIS and Battelle.

COMSIS Guidelines (1996) – 174 pages

Topic	Example Subtopics
General Guidelines	levels of warning, auditory/visual/tactile displays
Blind Spot Warning Devices	levels of warning, detection zone, display location
Backup Warning Devices	levels of warning, detection zone, display location
Driver Alertness Monitoring Devices	operating characteristics, display location
Headway Warning Devices	levels of warning, detection zone, hazard direction

Battele Guidelines – 184 pages

Topic	Example Subtopics
General Guidelines for Warning Design	prioritizing warnings, integrating warnings, false warnings
Auditory Warnings	when to use, determining the appropriate signal, speech warnings
Visual Warnings	when to use, determining the appropriate type of display
Haptic Warnings	when to use, determining the appropriate type of display
Controls	control type, compatibility, coding, labels
Forward Collision Warnings	design of visual, auditory, and haptic FCWs
Lane Change Warnings	design of visual, auditory, and haptic LDWs
Road Departure Warnings	design of lane drift and curve speed warnings
Heavy Trucks and Buses	Is there supposed to be something here?

Four recent studies of crash warnings are highlighted in this report, SAVE-IT, IVBSS, CWIM, and Jeong and Green.

Study	Key Points
SAVE-IT Project	* Smith and Zhang (2004) literature review is most relevant * describes warning triggering algorithms * more research on this topic since 2004 * project supports value of adaptive interfaces (that consider workload and where the driver is looking when they should be warned)
IVBSS Project	* only major study to look at integrated warnings (which emphasizes the need to consider how selection of light/sound/vibration for one warning affects responses to other warnings * included laboratory and simulator experiments as well as on-road evaluation * major on-road test (>100 drivers) consider only 1 set of alternative warnings
Crash Warning Interface Metrics (CWIM)	* idea of using lane shift to induce a lane change * LDW: Auditory warning and steering torque led to same performance * FCW: seat belt or seat belt with HUD or auditory led to fewest crashes * provides review of Advanced Collision Technologies (ACAT) project
Jeong and Green (2012)	very comprehensive summary of 17 studies covering 27 human factors experiments concerning forward-collision warnings

There are more studies of forward crash warning than any other type. Jeong and Green (2012) is the most extensive, as it is a literature review.

Study	Key Points

Chun, Han, Park, Seo, Lee, Choi (2012)	haptic steering wheel reduced response time the most followed by haptic seatbelt
Jeong and Green (2012)	summarized elsewhere, the definitive summary of FCW to date
Koustanaï, Cavallo, Delhomme, and Mas (2012)	familiarity with FCW improved performance
Muhrer, Reinprecht, and Vollrath (2012)	providing FCW+ (some automatic braking) reduced crashes over no warning
Alves, Goncalves, Rossetti, Oliveira, and Olaverri-Monreal (2013)	examined icons shown on HUD

Which modality is best for a lane departure warning depends on the study. Sometimes a haptic warning is best. Sometimes there are no modality differences.

Study	Key Points
Suzuki, and Jansson (2003)	No difference between mono and stereo beep in response time No difference in response time between various steering wheel vibrations and torque in response time, but vibration was more effective for drivers who did not know the meaning of the warning
Kozak, Pohl, Birk, Greenberg, Artz, Blommer, Cathey, and Curry (2006)	Response times were steering wheel vibration, rumble strip sound, HUD in increasing order Vibration + torque was most effective
LeBlanc, Sayer, Winkler, Ervin, Bogard, Devonshire, Mefford, Hagan, Bareket, Goodsell, and Gordon (2006)	LDW increased turn signal use
Green, Kang, Alter, Best, and Lin (2010)	Torque has shortest response time, followed by pulsed vibration, then continuous vibration
Dass, Uyttendaele, and Terken (2013)	No difference between auditory and haptic warning in number of lane departures.

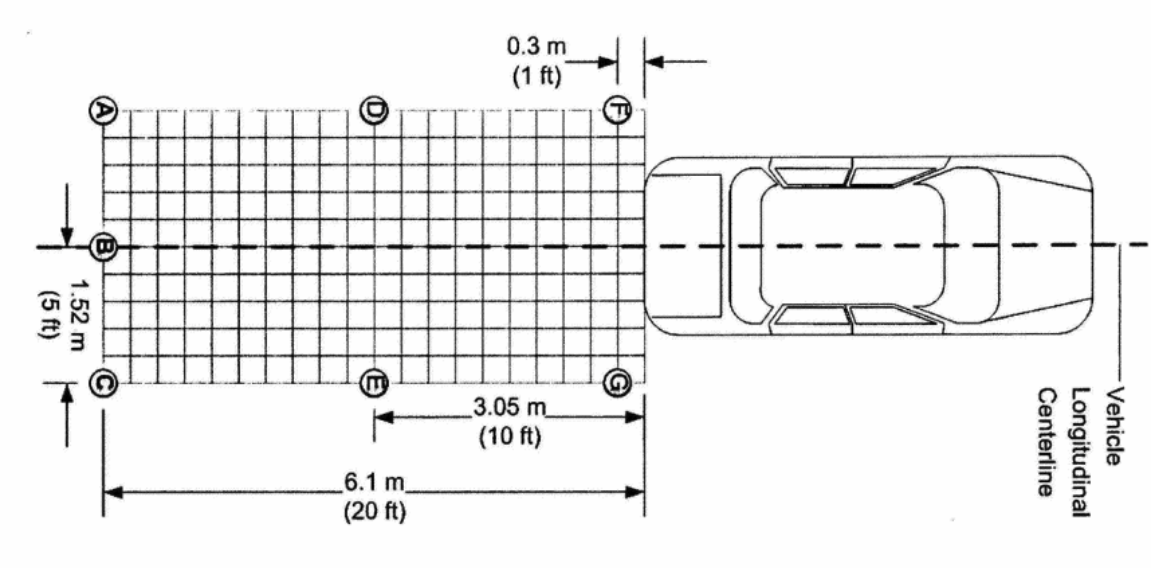
Blind Spot/Lane Change/Merge Warnings are clearly helpful, and interestingly, 1 study found that a nonplanar mirror was better than various warning system alternatives.

Study	Key Points
Campbell, Hooey, Carney, Hanowksi, Gore, Kantowitz, and Mitchell (1996)	Many alternatives described On dash visual display was thought to be most noticed but this point is based on preference not performance data from responding to warnings
Lee, Olsen, and Wierwille (2004) Also Olsen (2004)	Characterizes normal lane change timing

Kiefer and Hankey (2008)	LEDs in mirrors led to more mirror glances
Guo, Wotring, and Antin (2010)	Nonplanar mirror had fewer crashes than various proximity warning systems
Chun, Lee, Park, Seo, Choi, and Han (2013)	Steering wheel feedback prevented more crashes than seat belt warning

The best studies of backing warnings have examined how drivers back up. Research has shown that automatic braking systems for backing are beneficial, as are camera images. Their coverage is specified in FMVSS 111.

Study	Key Points
Harpster, Huey, and Lerner (1996) See Lerner, Harpster, Huey, and Steinberg, (1997) for more information	Characterized how drivers back up
Alter and Green (2010)	Back up prevention system (which included automatic braking) stopped subjects farther from vehicles to the rear than warnings alone or no warning
Hurwitz, Pradhan et al. (2010)	Only a few drivers look at rear camera before backing, but almost half did after an auditory warning
Kim, Rauschenberger et al. (2012) Also Heckman et al. (2012)	In terms of avoiding obstacles, there was no difference due to display size or location. However, mirror displays led to shorter response times than a center console display of any size
Kochhar, Talamonti, and Tijerina (2012) A~~See a~~lso see Kochhar, Talamonti, and Tijerina (2013)	With automatic braking, almost all subjects had ~~with~~ their foot on the brake in less than 1 s of brake activation Within 3 s of braking (when autobraking is released) all subjects had looked at the camera image
Kidd, Hagoski, Tucker, and Chiang (2014)	In terms of minimizing the number of objects, struck camera ~~-~~ and camera + sensor gave led to best performance Object in shade was always struck



Required area to be seen per FMVSS 111.

Research on in-vehicle intersection warnings has been limited, especially those warning about stop sign and traffic signal violations.

Study	Key Points
Neale, Perez, Lee, and Doerzaph (2007)	1-3 brake pulses led to more desired stopping performance than verbal warnings
Green, Schweitzer, and Alter (2008).	Examined traffic signal image with digital countdown that was responded to well

Even though people are extremely afraid of dying in a car fire, there is almost no research on how drivers should be warned about them.
Driving too fast is a common cause of crashes, and active pedals that provide force feedback, and have as steep increase when a speed threshold is reached, reduce instances of speeding/driving too fast for conditions.

Study	Key Points
Varhelyi and Makinen (2001)	For free flow, high speed (expressway type) driving, pedal force feedback reduced speed
Hjalmdal and Varhelyi (2004)	Pedal force feedback increased time gaps
Varhelyi, Hjalmdahl, Hyden, and Draskoczy (2004)	Pedal force feedback shifted speed distribution to lower speeds
Adell and Varhelyi (2008)	Drivers were satisfied with pedal force feedback
Adell, Varhelyi and Hjalmadahl (2008)	Pedal force feedback (active pedal) reduced speed more than beep when over the speed limit

Jamson, Hibberd, and Merat (2013)	Most fuel efficient driving occurred when a desired change in pedal position was accompanied by a step up in force and then a ramp up in force required, not just a ramp up Report contains force levels, not the case for some reports on active pedals

Literature on horn use, other than as an indicator of aggressiveness, does not appear to exist. Some thought needs to be given as to how horns can become a more effective communication device, such as flashing the lights when the horn is sound to attract attention. (Don't hit me.)

Based upon the literature and the author's expertise, there are some conclusions that emerge, but there are gaps as well.

1. Usually warnings, no matter how they are implemented, reduce crashes.
2. The focus has been on between modality comparisons, but it is unknown if the example in each modality chosen is optimal. Studies within modalities are rare.
3. The most important purpose of a warning is to alert the driver of something of which they are unaware, orient them to its location, and, if needed, tell them what to do.
4. Responding to multiple warnings, except for backing, is not an issue as multiple warnings are rare, and often the consequence of a response to a warning. (There is a forward crash warning. The driver swerves and triggers a lane departure warning.)
5. There is no stereotype for tones as warnings. Consider non-harmonic sounds that have a negative association.
6. Constraining warning to 2 stages is not necessary. Rather, considering grading them as is the case for auditory backing warnings, which beep more rapidly as an object is approached.
7. There are very few models and theories of warnings that provide quantitative predictions of their effectiveness.
8. Seat belt pre-tensioners as warnings need greater attention as they are often the most effective warning.

Based on what is known, a candidate warning system framework is proposed. The scope of this review did not allow for a complete review of the relevant literature.

1. If a hazard is detected, a non-pure tone is presented. If there are 2 hazards and the driver is back, then 2 alternating sounds are presented. Otherwise, only 1 sound is presented.
2. At the same time, an LED is illuminated in the direction of the hazard.
3. As the hazard increases, the repetition rate of the sound increases.
4. When a crash becomes imminent, the seat belt pre-tensions.
5. For backing up, a camera image is provided.

6. When the problem becomes severe, the vehicle should intervene by braking, or in the case of lane departures into another vehicle, providing some corrective steering.
7. For future systems, augmented reality should be considered to provide warnings.

TABLE OF CONTENTS

INTRODUCTION 1

METHOD 2

WHAT KINDS OF CRASHES ARE THERE AND FOR WHAT SHOULD WARNINGS BE PROVIDED? 3

WHAT ARE THE CHARACTERISTICS OF A GOOD WARNING? 14

WHAT ARE SOME OF BEST KNOWN MOTOR VEHICLE WARNING GUIDELINES? 16

SELECTED RECENT STUDIES OF CRASH WARNINGS 20

FORWARD-CRASH WARNINGS 25

LANE DEPARTURE WARNINGS 31

BLIND SPOT/LANE CHANGE/MERGE WARNINGS 35

BACKING WARNINGS 41

INTERSECTION WARNINGS 45

FIRE WARNINGS 47

DRIVING TOO FAST WARNINGS 48

HORNS AS WARNING DEVICES 51

WARNINGS SYSTEM FRAMEWORK 53

REFERENCES 57

INTRODUCTION

Traffic Safety Facts, the definitive report on that topic for the U.S., states that 30,800 people died in motor vehicle crashes in the U.S. in 2012, the latest year for which detailed statistics are available at this time (U.S. Department of Transportation, 2013). Many of the crashes associated with these deaths could be prevented if the drivers involved were warned of the impending crash.

To support the development of those warnings, numerous Society of Automotive Engineers (SAE) and International Standards Organization (ISO) standards and recommended practices have been developed. Those documents were reviewed in a previous report to the sponsor (Jeong and Green, 2013) and are not summarized here.

This report describes some of the key articles and reports in the human factors literature on warnings for motor vehicles as required by the project contract. This report focuses on what warnings are needed for, what makes a good warning, existing warning guidelines, and warnings for specific purposes (e.g., forward crash), with application to passenger cars, light trucks, vans, and sport utility vehicles. Those sections concern warning format (the modality used, the warning intensity, etc.), the intended emphasis of this report, not the timing of the warning (how soon before the crash should the warning be triggered). Readers should be aware that the literature on timing is extensive (e.g., Lee, McGehee, Brown, and Reyes, 2002; Kiefer, Cassar, Flannagan, LeBlanc, Palmer, Deering, and Shulman, 2003; Kiefer, LeBlanc, and Flannagan, 2005; Nakaoka, Raksincharoensak, and Nagai, 2008), especially for forward crash warning. Ideally, had the resources been available, this review would have covered each warning system, both in terms of content and timing, to the level of detail in Jeong and Green (2012). Based on the information reviewed and expert opinion, a framework for warnings was developed.

More specifically, this report examines the following questions:

1. How often do various types of crashes occur and under what circumstances do they occur? What are the implications for warning design?
2. What are the characteristics of a good warning?
3. What are some of the major guidelines concerning crash-warning design?
4. What is some of the recent research on crash warnings?
5. What are some of the major findings with regard to specific crash warning systems (e.g., forward crash warning, lane departure warning, back up warning, lane change/blind spot warning)?
6. Based on the information gathered and expert opinion, what could be a framework for motor vehicle warnings?

METHOD

To complement the first author's knowledge of the literature and reports he has completed, the studies listed in the statement of work were examined.

In addition, other relevant studies were identified using Google Scholar, though some were identified using Google. This was done primarily for sections concerning specific systems, for example forward crash warning. For those sections, the section name was searched (e.g., forward crash warning) along with variations where the word "collision" replaced "crash." Where appropriate, other variations of the section name were examined (e.g., backing vs. backup). Also, include terms such as "human factors" and "driver interface" were sometimes included to identify relevant publications. Publications given the greatest attention were those near the beginning of the list provided by Google Scholar, though publications with a high number of citations were give special attention.

When a potentially relevant publication was found, the publication was downloaded. Next, its abstract was read and if needed the publication was skimmed to verify its relevance. If indeed it was useful, then the publication was read more carefully and the author list was examined for other relevant citations to check for prior references (backward referencing). In addition, for highly relevant publications, the "cited by" entry in Scholar was examined to identify newer references (forward referencing).

As a reminder, this review is not exhaustive given its intention and resources. Therefore, there were many instances where there were articles that were not the most central or recent, and therefore, are not reviewed here.

WHAT KINDS OF CRASHES ARE THERE AND FOR WHAT SHOULD WARNINGS BE PROVIDED?

By identifying crashes with common characteristics, the scope of various types of crashes and opportunities for developing countermeasures may be identified. One of the earliest known typologies was that of Massie, Campbell, and Blower (1993) (Figure 1), which was expanded from the coding used in the National Accident Surveillance System (NASS) of the U.S. Department of Transportation.

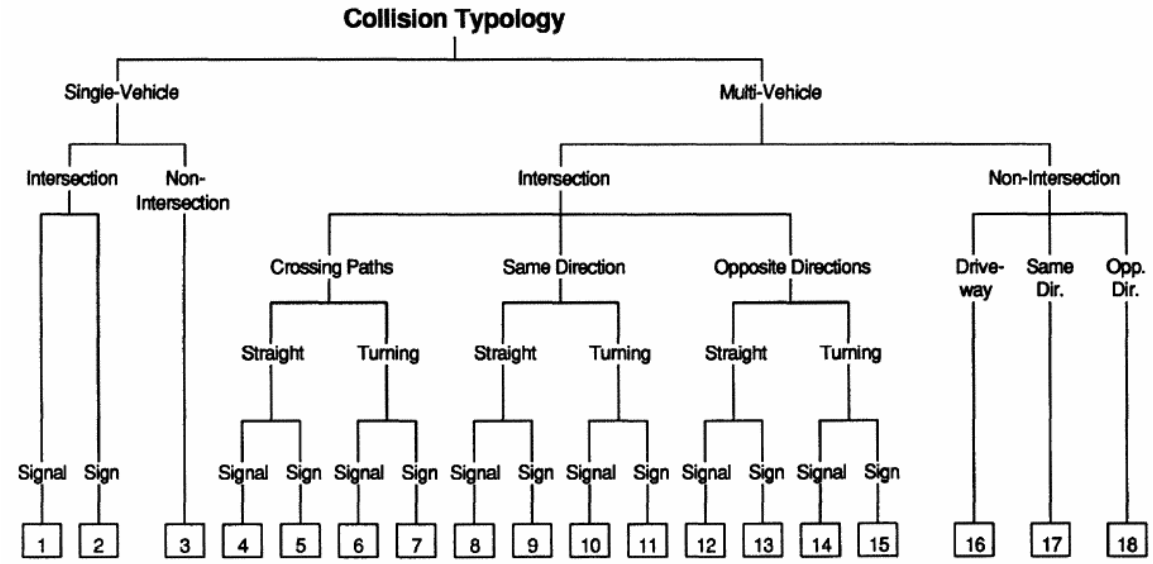


Figure 1. Massie, Campbell, and Blower (1993) Collision Typology
Source: Massie, Campbell, and Blower (1993), page 245.

As part of collaboration between UMTRI and General Motors, the 44-crashes typology was developed, which was based on NASS and a detailed examination of a limited data set of crashes (Campbell, Wolfe, Blower, Waller, Massie, and Ridella, 1990; General Motors, 1997). Those 44 crash types represent the full set of all the crashes that exist and carries over ideas from the Massie, Campbell, and Blower typology.

The most commonly used crash typology currently is described in detail in Najm, Smith, and Yanagisawa (2007) and more briefly in Najm and Smith (2007). Accordingly, that analysis is used here. Using the Najm, Smith, and Yanagisawa typology, Table 1 was created. That table shows the scenario number, the relative frequency of the crash in the data base from which it was created, an abridged name for the scenario (to fit in the space available), a brief description of the scenario, and if a warning is to be provided, what the warning should concern. Readers should know that crash priorities could be determined not only using the frequency data provided, but also data for economic cost, the number of years of life lost, or other statistics. The frequency data are provided to indicate that the crashes listed are not of equal importance. What is to be

warned about is based upon the opinions of the authors of this report, primarily the first author. The page number in the Najm, Smith, and Yanagisawa report is listed to aid those seeking additional information concerning each scenario. In theory, if there were warnings that covered all cases of each scenario, then there would be some type of warning for every possible crash.

Table 1. 37 Crash Scenarios

#	Page	Rel. Freq.	Scenario Name	Scenario Description	Warn About
1	28	0.71	Vehicle Failure	tires/brakes/steering/drivetrain fails; day, dry road, clear weather, may be on curve	vehicle maintenance
2	29	1.73	Control Loss w/ Prior Vehicle Action	turning at intersection & runs off road; clear weather, wet/slippery, may also be decelerating or changing lanes	slippery road, stability control
3	30	8.90	Control Loss w/o Prior Vehicle Action	55 mph posted, often curve, rural, wet/slippery, dark, bad weather	slippery road, stability control
4	31	4.27	Running Red Light	urban, inattention, other vehicle crossing at 90 deg, also left turn	traffic signal violation
5	32	0.81	Running Stop Sign	could occur if turning; rural, inattention, clear weather, 35 or less posted	stop sign violation
6	33	1.14	Road Edge Departure w/ Prior Maneuver	depart road turning at intersection; rural, night, clear, 25 mph posted	LDW
7	34	5.62	Road Edge Departure w/o Prior Maneuver	going straight & loses control; wet/slippery, >=55 mph posted, rural	LDW
8	35	1.11	Road Edge Departure while Backing Up	driveway/alley; urban, daylight, 25 posted	LDW in reverse
9	36	0.39	Animal Crash w/ Prior Maneuver	leaving parking or passing vehicle; rural, night, clear, may be slippery	animal
10	37	5.13	Animal Crash w/o Prior Maneuver	going straight; rural, night, clear, 55 mph posted	animal
11	38	0.29	Pedestrian Crash w/ Prior Maneuver	turning left at intersection, ped in crosswalk, signalized intersection; urban, vision obstructed, also right turn, ped is running or playing	pedestrian (kids)
12	39	0.66	Pedestrian Crash	going straight, ped not at intersection; 25	obstructed

			w/o Prior Maneuver	mph posted, dark, vision obscured, may be adverse weather	pedestrian
13	40	0.31	Cyclist Crash w/ Prior Maneuver	turning right at intersection; 25 mph, clear, also turn left, bike in crosswalk	bike on side
14	41	0.41	Cyclist Crash w/o Prior Maneuver	going straight & bike at intersection; clear, 25 mph posted, vision obscured	bike not visible
15	42	2.20	Backing Up into Another Vehicle	backing in alley or driveway into another vehicle; clear, 25 mph, day	vehicle behind or to side
16	43	3.73	Vehicle(s) Turning – –Same Direction	turn left, cuts into another vehicle in same direction; 35 mph, also to right	no gap
17	44	0.81	Vehicle(s) Parking – Same Direction	leaving parking & encounters vehicle in same direction; 25 mph	no gap
18	45	5.69	Vehicle(s) Changing Lanes – Same Direction	urban, >=55 mph, day	no gap
19	46	1.65	Vehicle(s) Drifting – Same Direction	straight, urban, clear, >=55 mph	LDW
20	47	0.22	Vehicle(s) Making a Maneuver – Opposite Direction	passing & head on crash; rural, 55 mph, clear	no gap
21	48	2.08	Vehicle(s) Not Making a Maneuver – Opposite Direct.	2 lane road & drift into opposing traffic; 55 mph, clear	drift of other vehicle
22	49	1.44	Following Vehicle Making a Maneuver	changing lanes and closes on lead vehicle; day, 55 mph posted	FCW
23	50	0.32	Lead Vehicle Accelerating	near intersection; urban, clear, 45 mph posted, dry	FCW
24	51	3.53	Lead Vehicle Moving at Lower Constant Speed	day, clear, posted 55 mph	FCW
25	52	7.20	Lead Vehicle Decelerating	following lead vehicle; rural, day, clear, 55 mph	FCW
26	53	16.41	Lead Vehicle Stopped	lead is approach traffic control device or slowing to turn; 35 mph, clear	FCW

27	54	3.71	Left Turn Across Path From Opposite Direction at Signalized Junctions	either subject or other vehicle is turning; 35 mph	no gap
28	55	0.59	Turning Right at Signalized Junctions	driving straight, right turning vehicle into path; clear, 35 mph posted	run light
29	56	3.19	Left Turn Across Path From Opposite Directions at Non-Signalized Junctions	subject or other vehicle turning left, one going straight; 35 mph posted, also driveways	no gap
30	57	4.44	Straight Crossing Paths at Non-Signalized Junctions	at stop sign, stops and cuts across traffic; 25 mph posted	wait for stop
31	58	7.32	Turning at Non-Signalized Junctions	turn (L or R, usually L) & strikes/struck by crossing traffic; 35 mph posted	gap in traffic, turning vehicle
32	59	0.22	Evasive Action W/ Prior Maneuver	vehicle is turning left and maneuvers to avoid object; 35 mph	obstacle to avoid
33	60	0.95	Evasive Action W/o Prior Maneuver	vehicle is going straight and maneuvers; 35 mph posted	obstacle to avoid
34	61	0.77	Non-Collision Incident	fire starts; rural, day	fire
35	62	0.51	Object Crash W/ Prior Maneuver	leaving parking at night and strike shoulder; 25 mph posted, dark, wet	obstacle at night while turning
36	63	0.92	Object Crash W/o Prior Maneuver	pothole, post; straight on rural road, night, >= 55 mph	obstacle at night while going straight
37	64	0.60	Other	no driver, hit and run, general lack of data	

Further consideration of these crash scenarios and the types of warnings needed suggested that crashes could be grouped into a smaller number of categories, primarily by maneuver, for the purpose of designing warnings (Table 2). In the sections that follow, each of these categories is discussed and ~~suggested~~ warning design recommendations are provided for each category. Notice that scenarios related to slippery and driving too fast (2, 3, 6, 7) are not included in this table because that problem occurs in all situations. They are included in a later table.

Table 2. Common Crash Scenario Groups

Maneuver	Warn About	Scenarios
driving straight, usually but not always expressway	objects ahead (slow, stopped, changing lanes)	20, 21, 24, 25, 26, 33, 36
driving straight	drifting from lane (or other vehicles drift)	6, 7, 19, 35
changing lanes	other vehicles	16, 17, 18, 22
driving straight and approaching intersection	other vehicles/objects at intersection	13, 14, 16, 23, 27, 28 29, 30, 31, 32
approaching intersection	missed stop sign or traffic signal (at intersection)	4, 5
backing up	other vehicles, leaving lane, exiting parking	8, 15
driving straight or turning	hidden/obstructed bike, animal, pedestrian, all especially at night	9, 10, 11, 12, (maybe 13, 14)
all	fires, submerged (and make exit easy	34
all	vehicle failure	1

Another related table (Table 3) that characterizes the crash situation is drawn from the National Motor Vehicle Crash Causation Survey (NMVCCS, U.S. Department of Transportation, 2008) presents data on how often various factors led to crashes based on an in-depth weighted sample of real crashes. Notice that the most common situation is maneuvering at an intersection, more than 1/3 of the crashes.

Table 3. Critical Pre-Crash Event of Vehicles

Critical Pre-Crash Event		Weighted Percentage
Vehicle traveling	turning or crossing at intersection	36.2
	off the edge of the road	22.2
	over the lane line	10.8
	others	0.7
	Subtotal	69.9
	stopped	12.2

Other vehicle in lane	traveling in same direction	4.8
	traveling in opposite direction	0.1
	others	0.1
	Subtotal	(=17.2)not17.3
Vehicle control loss	traveling too fast	5.0
	poor road condition	2.0
	vehicle problem	1.2
	others	0.7
	Subtotal	8.9
Other vehicle encroachment	from crossing street	0.5
	from adjacent lane	0.5
	from opposite direction	0.3
	from driveway	~ 0
	Subtotal	1.3
Object or animal		1.4
Others		1.1
Unknown		0.1
Total		100.0

Source: Adapted from U.S. Department of Transportation, 2008, page 23.

Two other tables from NMVCCS deserve attention. In Table 4, showing driver related critical reasons, notice that inattention and distraction are major contributors to crashes (almost 40 according to this data set), and 13 are associated with driving too fast for conditions/curve. These two causes are highlighted because warnings for them could be provided.

Table 4. Driver-Related Critical Pre-Crash Events.

Critical Reason for Critical Pre-Crash Event		**Weighted Percentage**
Recognition error	inadequate surveillance	20.3
	internal distraction	10.7
	external distraction	3.8
	inattention (i.e., daydreaming, etc.)	3.2
	other/unknown recognition error	2.5
	Subtotal	(=40.5) not 40.6
Decision error	too fast for conditions	8.4
	too fast for curve	4.9
	false assumption of other's action	4.5
	illegal maneuver	3.8
	misjudgment of gap or other's speed	3.2
	following too closely	1.5
	aggressive driving behavior	1.5

	other/unknown decision error	6.2
	Subtotal	(=34) not 34.1
Performance error	overcompensation	4.9
	poor directional control	4.7
	other/unknown performance error	0.4
	panic/freezing	0.3
	Subtotal	10.3
Non-performance error	sleep, actually asleep	3.2
	heart attack or other physical impairment	2.4
	other/unknown critical nonperformance	1.6
	Subtotal	(=7.2) not 7.1
Other/unknown driver error		7.9
Total		100

Source: Adapted from U.S. Department of Transportation, 2008, page 25.

Finally, notice that in Table 5, where roadway and atmospheric conditions are critical reasons for crashes, slick roads predominate as a cause.

Table 5. Critical Reasons for Pre-Crash Events Due to Roadway and Atmospheric Conditions

Critical Reason for Critical Pre-Crash Event		**Weighted Percentage**
Roadway	slick roads (ice, loose debris, etc.)	49.6
	view obstructions	11.6
	signs/signals	2.7
	road design	1.4
	other highway-related condition	9.8
	Subtotal (Roadway)	(=75.1) not 75.2
Atmospheric Conditions	fog/rain/snow	4.4
	other weather-related condition	4.0
	Subtotal (Weather)	8.4
	glare	16.4
Total		100.0

Source: Adapted from U.S. Department of Transportation, 2008, page 26.

Collectively, these suggest that a general warning strategy should consider the following.

- objects ahead, normally when driving straight, a potential enhancement of current FCW systems
- drifting from the current lane, the current LDW systems
- changing lanes, merging
- intersection warning system, some of which have been proposed but for which considerable interface development is needed
- a more comprehensive approach to backing up other than a small display that draws driver attention to inside the vehicle with markings that have no meaning to drivers
- warnings for objects drivers cannot see
- warnings for vehicle fires (and maybe automatic extinguishers for them)
- warnings that indicate when the surface is slippery in a more effective and specific manner coupled with systems that indicate when the driver is going too fast.

The key is making the system broader in its coverage than current systems and more specific. For example, currently systems that warn about slippery roads rely primarily on ambient temperature, though some provide feedback after wheel slippage has occurred. A better system would tell drivers when they are likely to encounter a slippery section, and for example, make specific suggestions for speed.

WHAT ARE THE CHARACTERISTICS OF A GOOD WARNING?

There are many books (e.g., Lehto and Miller, 1986; Edworthy, 1996; Miller, Lehto, and Frantz, 1990; Peters, and Peters, 1999; Miller and Lehto, 2001; Laughery, 2006; Wogalter, 2006; Wogalter, Laughery, and Mayhorn, 2012) and journal articles (e.g., Ursic, 1985; Latin, 1993; Laughery, Wogalter, and Young, 1994; Wogalter, Conzola, and Smith-Jackson, 2002) that generally concern warning design or warning design for specific applications (e.g., Frantz and Rhoades, 1993; Davis, Wolf, Bass, Thompson, Tilson, Neuberger, and Parker, 2006; Shrank, Avorn, Rolon, and Shekelle, 2007; Tebeaux, 2010). Those reading this report may find many of those documents useful.

Given that vast body of literature, what are the characteristics of a good warning? They are that the warning (1) is visible/apparent, (2) is legible/audible, (3) conveys the appropriate urgency of the problem or the response, (4) tells the user what is wrong, (5) tells the user what to do, and (6) the meaning is apparent without training or explanation, or if not at least easily learned. The nature of characteristics (1) and (2) may depend upon the modality use for the warning and in some cases may not be separable. In terms of 4 and 5, the error and corrective action, there may be cases where one or the other of these two characteristics makes the other obvious, but that could depend on the knowledge of the user of the system in question. If a warning must be apparent the first time it is presented, or if learning is an option will depend upon the warning. If it is important the warning be responded to the first time, then there may not be an opportunity for learning.

For text warnings in motor vehicles, Damouth and Green (1997) present an expanded list (Table 6). Although intended for text warnings shown on 1 or 2 lines, those developing warnings may nonetheless find this table useful as a checklist for a broader range of contexts.

Table 6. Warning Criteria from Damouth and Green (1997)

#	Criteria	Primary Question	Explanation
1	Under-standability	Do drivers understand the message (as indicated by the understandability data and/or their comments)?	Do drivers say they do not understand a particular word or abbreviation? When reading a message aloud, do people pause at the wrong place (incorrectly parse it) or have trouble pronouncing a word? Can the message be clarified by adding or removing punctuation, spacing, or line breaks?
2	Desired response	Do drivers carry out the wrong action or actions at the wrong time?	This includes turning something back on when it has been automatically shut off, seeking service too late or too soon, or looking in the manual when not necessary. Ideally, if messages are well designed, drivers should never have to look in a

			manual to determine what a message means.
3	Error feedback	Does the message tell the driver what is wrong?	This is especially challenging for systems unfamiliar to drivers.
4	Positive guidance	Does the message tell the driver what to do?	In some cases, due to lack of space, it may not be possible to report both the error and the guidance. What to present in that situation is context dependent.
5	Specificity	Could the driver interpret a message in more than one way?	For example, a fan fault message could refer either to the engine fan or a fan for the climate control system. In addition, there may be situations where messages report what is wrong (e.g., it is open) or what to do (e.g., open it) (the command-error problem).
6	Consistent format	Does the first line say what is wrong and the second line say what to do? Is the same message phrasing always used?	(1) In some cases the reverse order did not flow as well. What is most critical is that all messages be in the same order. (2) In terms of phrasing, do not use "engine temp high" in one place and "high engine temp" in another.
7	Continuation	Is a space provided for continuation lines?	If the problem description exceeds one line, the first character of the second line should be a space so the user knows it is a continuation and not an action. This is an exception to the consistent format guideline.
8	Temporal order	Does the first line say what to do first?	If there are multiple driver actions, they should be listed in the order the actions should be completed.
9	Common English	Are the terms in common American English?	Terms such as "boot" and "bonnet" should not be used. "Turn signal" is preferred to "turn indicator" and "open" to "ajar."
10	Minimum verbiage	Are the fewest characters used?	Time spent reading messages is time not spent looking at the road, so short messages are desired. However, short messages should not be provided at the cost of understandability.
11	Aesthetics	Does the message make the product look cheap?	This can result from the excessive use of contractions, spelling errors, or abbreviations (e.g., hi vs. high, lo vs. low).

WHAT ARE SOME OF BEST KNOWN MOTOR VEHICLE WARNING GUIDELINES?

Complementing that literature are two sets of guidelines identified in the proposal – the COMSIS and Battelle guidelines -- that are specifically applicable to motor vehicles. The documents are extensive, 175 and 184 pages, respectively. To give the reader a sense of their content, their tables of contents are reproduced in this section along with summary comments.

Lerner (1996) – COMSIS guidelines

The first comprehensive set of guidelines specifically concerning warnings motor vehicles is Lerner (1996), though they are predated by many other guidelines for warnings for a variety of contexts. Sometimes this document is referred to as the COMSIS guidelines, Lerner's employer. As summarized in Table 7, document includes both general guidelines that specify warning characteristics such as vocabulary for speech warnings and specific guidelines such as where a backup warning should be located.

Table 7. Outline of Lerner (1996) Guidelines

2.0 General Guidelines

2.1 Device Operation (activation/deactivation, testing)
2.2 Levels of Warning (imminent, cautionary)
2.3 Warning Presentation (e.g., prioritization, auto termination, prevent false warnings
2.4 Auditory Displays (cuing for directional hazards, sound source information auditory display characteristics (onset/offset, spectral characteristics, repetition, duration), speech display characteristics (message length, vocabulary, repetition, etc.), control of auditory display intensity, etc.)
2.5 Visual Displays (location, legibility, icons, characteristics (flash rate, size, color)
2.6 Tactile Displays (frequency, intensity, duration, pulse rate)
2.7 Controls/Adjustments (labeling, shape, size, texture)
2.8 User Documentation

3.0 Blind Spot Warning Devices

3.1 & 3.2 Device Application & Device Activation
3.3 Primary Visual Display Location
3.4 Levels of Warning
3.5 Detection Zone Characteristics (coverage)
3.6 Indication of Direction of Hazard
3.7 Termination of Warnings (automatic, manual)
3.8 Detector Sensitivity Adjustment

4.0 Backup Warning Devices - subheadings are similar to Blind Spot (sect. 3.0)

5.0 Driver Alertness Monitoring Devices

5.1 Device Application
5.2 Operational Characteristics (sensing, activation, calibration)
5.3 Warning Display Location
5.4 Levels of Warning (imminent, cautionary)
5.5 Termination of Warnings
5.6 Detector Sensitivity Adjustment

6.0 Headway Warning Devices

6.1 & 6.2 Device Application & Device Activation
6.3 Primary Visual Display Location
6.4 Levels of Warning
6.5 Control of False and Nuisance Warnings
6.6 Detection Zone Coverage
6.7 Indication of Direction of Hazard
6.8 Termination of Warnings
6.9 Controls/Adjustments

For each guideline, comments are provided in addition to the actual guideline. An example follows:

2.5.4.3 Visual Displays – Characteristics of Status Indicators - Flashing.
Flashing indicators should not be used to indicate the operational status of warning devices.

> Because of their superior conspicuity, flashing visual displays should be reserved strictly for imminent crash avoidance warning displays. Thus, flashing displays should not be used to indicate operational status of the device.

To a large degree, many of the guidelines are general statement that are as true now as when the report was written 18 years ago and will continue to be indefinitely into the future. For example, guideline 2.3.4 (Automatic termination of warnings) states, “The device that triggers a warning should terminate the warning automatically once the triggering condition no longer exists.” For that reason, it may be helpful for designers to create an abridged set of guidelines they can easily view. To do such, the comments will need to be omitted. Potentially, the roughly 80 pages of guidelines and comments could be reduced to a more easily managed 10 pages (or less).

However, readers should keep in mind that a great deal of research has been conducted since these guidelines were written, and many of them can now be more specific. For example, Guideline 6.9.2 (Headway Warning Devices – Controls/Adjustments - Criteria Adjustment) states, “A control may be provided to allow the driver to adjust the headway and time-to-collision criteria within a limited range. The driver should not be allowed to adjust the device below a minimum level to ensure

effectiveness." Notice that values for "limited range" and "minimum level" are not provided.

For additional information, see Lerner (1996)

Campbell (2007) – Battelle Guidelines

A follow up to those guidelines is Campbell (2007), sometimes referred to as the Battelle guidelines. To some degree, those guidelines were organized in a manner similar to those of Lerner (1996), considering general guidelines first, and then specific warning systems. Table 8 shows the contents.

Table 8. Outline of Campbell (2007) Guidelines

Chapter 2. General Guidelines for Warning Design
prioritizing warnings, integrating warnings, false warnings, warning timing, etc.

Chapter 3. Auditory Warnings
when to use, determining the appropriate signal, speech warnings, urgency and annoyance

Chapter 4. Visual Warnings
when to use, determining the appropriate type of display, warning characteristics

Chapter 5. Haptic Warnings
when to use, determining the appropriate type of display, warning characteristics

Chapter 6. Controls
control type, compatibility, coding, labels

Chapter 7. Forward Collision Warnings
design of visual, auditory, and haptic FCWs

Chapter 8. Lane Change Warnings
design of visual, auditory, and haptic LCWs

Chapter 9. Road Departure Warnings
design of lane drift and curve speed warnings

Chapter 10. Heavy Trucks and Buses

However, at a detailed level, these guidelines are structured, with each detailed guideline being 2-pages long and having a specific format showing the guideline title, the guideline itself, a rating of how much it was based on expert judgment vs. data, discussion, design issues, and references. Furthermore, each 2-page section has multiple related guidelines. For example, for warning timing (page 2-12) Campbell

states the following, “Warning timing for forward-acting CSWs such as FCW and Curve Speed Warning (CSW) systems should take into account expected driver response time and driver-selected deceleration levels. Warning timing for side-acting CSWs such as LCW and Lane Departure Warning (LDW) systems should be based primarily on when the system detects the driver’s intent to change lanes or on when it predicts a lane departure/conflict with a side hazard. Sensitivity settings may be provided that modify the baseline warning timing according to driver preference. However, these adjustments should be bounded by a minimum warning time that is based on kinematic conditions necessary to avoid a collision or hazardous situation.” The Campbell guidelines, in some places, are more specific than Lerner, et al, in part because with the passage of time there are more data available. However, in several instances, that specificity is in the discussion, not the guideline itself.

Thus, these existing guidelines provide useful information for selecting warnings for individual systems. However, they fall short in providing advice for integrated systems, primarily because those systems have not been tested, except for IVBSS as described in the next section. Further, there is a lack of research to optimize warnings within specific modalities.

For additional information, see Campbell (2007).

SELECTED RECENT STUDIES OF CRASH WARNINGS

The studies in this section are given special mention because of their particular importance, both in terms of how often they are cited and their results. In addition, when compared with other studies, their sample sizes are often larger and the test methods used ~~has~~ have been well documented.

SAVE-IT Project

One of the more underpublicized DOT projects is SAVE-IT (SAfety VEhicle(s) using adaptive Interface Technology), ~~whose~~ which, as its name suggests, conducted research to examine how interfaces that adapted to the driving situation could provide safety information, with a particular concern for distraction related crashes. (See http://www.volpe.dot.gov/safety-management-and-human-factors/surface-transportation-human-factors/safety-vehicle-using for more information.) Of the many project~~s~~ reports, for the research reported here, the Smith and Zhang (2004) literature review is most relevant.

The report provides a useful overview of the types of crashes that exist, and considers the major crash types (rear end, road departure, intersection, lane change/merge) and the literature relating to 4 warnings systems – forward collision, lane drift, stop sign violation, and blind spot. A major focus of the review is on the algorithms that could be used to determine when each warning should be triggered. Readers should keep in mind, that what is contained in this report needs to be supplemented by current literature, as a great deal of research has been completed on warning algorithms since 2004.

IVBSS Project

In the Integrated Vehicle Based Safety System (IVBSS) project, there were laboratory and field tests of a number of warning systems. Some of the findings related to the laboratory studies (Green, Sullivan, Tsimhoni, Oberhotzer, Buonorasa, Devonshire, Schweitzer, Baragar, and Sayer, 2008) are mentioned elsewhere in this report.

Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blankespoor, and Winkler (2011) describe the results of an on-road study involving 108 drivers and 16 instrumented cars with integrated crash warning systems (forward crash, lateral drift, lane change/merge, and curve speed). A total of 234,000 miles were driven. Each vehicle was driven for 6 weeks, 2 of which were baseline driving (no warnings). Almost 23,000 warnings were triggered. The driver interface consisted of displayed text (in most cases, shown on the top of the center stack) and other information as shown in Table 9.

Table 9. Warnings in the IVBSS Light Vehicle Field Test

Warning	Visual Display	Other Warning

FCW	“Hazard Ahead” text	Tone (# 1), brake pulse
CSW	“Sharp Curve” text	Tone (#1)
LDW caution	“Left Drift” or “Right Drift” text	Directional seat vibration
LDW imminent or LCM	“Left Hazard” or “Right Hazard” text	Direction tone (#2)
BSD	LED in mirror	none

Drivers reported all of the warnings attracted their attention (typically just over 6 on a 1 (strongly disagree) to 7 (strongly agree) scale), but several mentioned they were startled/alarmed by the brake pulse. The warnings were rated as not distracting. The later warning decreased the number of lane departures (from 15.9 to 7.1/100 miles on limited access roads and 13.7 to 8.4 on surface streets). There were no differences in the number of FCW warnings per 100 miles (both 0.1/100 miles for limited access roads and 0.6/100 miles for surface streets). Similarly, the number of curve speed warnings was identical (0.1/100 miles) for both conditions (limited access roads, surface streets). Furthermore, turn signal use increased when the LDW was enabled (from 71.4% to 94.0% of the lane changes). The primary value of the IVBSS project is that it showed that a particular set of warnings could be quite effective.

Crash Warning Interface Metrics (CWIM)

One recent project of note in summarized in Lerner, Jenness, Robinson, Brown, Baldwin, and Llaneras (2011), the so-called CWIM (pronounced Sh-wim) project. The project was concerned with the evaluation of warning characteristics (such as modality) on warning effectiveness as well as developing methods to assess them. Of particular concern was how between-vehicle differences in how warning systems are implemented (what they called driver interface variability) could influence warning system effectiveness. Five experiments related to this project were conducted, 4 of which are described here.

In the first of 5 experiments, 90 subjects drove a 2-lane rural road simulated in the National Advanced Driving Simulator (NADS) and were periodically distracted by reaching back to a touch screen. At 3 points in the drive a lane shift was induced without motion cues. Auditory and haptic warnings and 2 types of steering torque all led to lane departures (as measured by their area) representing roughly equal performance, though all were superior to no warning.

A second NADS experiment involved 32 subjects periodically responding to stopped and slow moving lead vehicles. In comparing passive (HUD and auditory alert) with an active warning system (brake pulse), the passive system led to much greater adjusted time to collision, probably because drivers were startled by the brake pulse. For other performance statistics, differences between interfaces were generally small.

In a The third experiment, was conducted at a NHTSA test track involving 64 subjects. They followed a lead vehicle and also performed a distracting secondary task. FCW systems using a HUD, beep, seatbelt tensioner, and combinations of them were

examined. Near the end of the experiment, the lead vehicle left the travel lane, revealing a stopped vehicle. The belt alone led to the fewest number of collisions of the single warning interfaces, and combining the belt with another crash warning reduced crashes further. Having all 3 warnings was not the best.

To examine what happens when warning signals change, 60 subjects in an unspecified driving simulator responded to auditory forward crash warnings from the IVBSS project as well as 4 scenarios from that project (lead vehicle suddenly decelerates, lane change and lead vehicle decelerates, stopped vehicle revealed by lane change, and cut in). There were 2 experimental sessions in which the driver interface remain fixed, and performance improved over time. In the third session (day 3), subjects were told the simulator was changed and responded to other auditory warnings from the IVBSS project (heavy truck) if they responded to light vehicle warnings or vice versa. Generally, drivers continued to improve with practice except when the switched from the heavy vehicle warning to the light vehicle warning on day 3. Of the 2 warnings from the IVBSS project, neither of them clearly led to shorter brake response times.

The CWIM final report also reviewed the Advanced Crash Avoidance Technologies (ACAT) test protocols. As the focus of this report is on warning design, the reader should see the CWIM report for details. In addition, the ACAT studies contain a large number of evaluations of interfaces, often varying in modality between alternatives. As the ACAT research is well summarized in the CWIM report, those summaries are not repeated here.

In general, the CWIM project slightly favors weak steering wheel torque for lane departure warning, HUD plus belt pre-tensioner for forward crash warning, but also suggests that a brake pulse should be considered.

Jeong and Green (2012)

A more recent but not well-known study is Jeong and Green (2012). That literature review summarizes 17 studies covering 27 human factors experiments concerning forward-collision warnings. For the purposes of this section, what matters most is the overview of studies conducted, Table 10. Notice the wide variety of combinations explored, with not much focus on optimizing warnings within modalities.

For additional information, readers are encouraged to examine the results in Jeong and Green (2012).

Table 10. Warning Modality Combinations Examined

Study		No Warn-ing	Unimodal			Multimodal			
			Auditory	Visual	Tactile	Auditory +Visual	Auditory +Tactile	Visual +Tactile	Auditory + Visual + Tactile
1	Baldwin (2011)		Ab	W					
2	Baldwin & May (2011)	X		W		Ab+W			
3	Cheng et al. (2002)		Ab						
4	Curry et al. (2010)	X	UNK	UNK		UNK			
5	GM & Dephi-Delco (2002)	X		Ab, I		Ab+I			Ab+I+V
6	Graham (1999)		Ab, I, W						
7	Gray (2011)	X	I						
8	Ho et al. (2006)	X			V				
9	Ho et al. (2007)	X	Ab		V		Ab+Ab		
10	Kiefer (2000)	X	Ab, W	Ab	V		Ab+Ab	Ab+V	
11	Kiefer et al. (2005)	X				Ab+I			
12	Lee et al. (2004)	X	Ab		V	Ab+Ab		Ab+V	
13	Lee et al. (1997)	X				Ab+Ab			
14	Ljung et al. (2007)	X			V	Ab+W			
15	May & Baldwin (2006)	X	Ab, W						
16	McGehee et al. (2002)	X	UNK						
17	Rosario et al. (2010)			Ab	V				

Where:

Modality	Abbreviation	Modality	Abbreviation
Auditory	Ab (Abstract = tone), I (Iconic sound), W (Word, spoken)	Vibration	V (Vibration)
Visual	Ab (Abstract = light), I (Iconic), W (Word)	Others	UNK (Unknown), X (None)

FORWARD-CRASH WARNINGS

Forward collision warning (FCW) systems alert drivers to vehicles in front of them that are slowing or stopping, when vehicles in adjacent lanes cut in front of them, or when the subject vehicle cuts in behind a vehicle close to them. Some FCW systems also included automatic braking systems to prevent forward crashes, which are sometimes referred to as FCW+. The research conducted to date (of which examples appear in Table 11) primarily concern the location of visual warnings, the format for auditory warnings, and if visual, auditory, or haptic warnings are more effective. For an interesting alternative to traditional warnings that uses augmented reality, see Park and Kim (2014).

Table 11. Selected papers on Forward Collision Warning Systems

Study	Subjects	Procedure	Findings
Chun, Han, Park, Seo, Lee, Choi (2012)	24 Male Drivers (ages 30-40 and 50-60)	in a driving simulator with a haptic seatbelt and haptic steering wheel. Drivers followed a lead vehicle at 80km/hr and 40 m. Also performed a secondary task (entering 7-digit number on a touch screen).	• Haptic steering wheel reaction time decreased from 1.75 s to 1.48 s. • Haptic seatbelt reaction time decreased from 1.75 s to 1.54 s. • FCWs reduced the braking distance by 6.13 m. • Haptic steering wheel increased the collision prevention rate from 0.17 to 0.42 and the haptic seatbelt increased to 0.33.
Jeong and Green (2012)	Varied with study	17 studies with 27 experiments were identified using UMTRI Library and Google Scholar; 23: used driving simulators; 4 were on test tracks in most studies, subjects followed a lead vehicle that braked unexpectedly triggering visual, auditory, or haptic warnings.	• For response/reaction time see Table 12 • For crashes see Table 13 • For additional information see report.
Koustanaï, Cavallo, Delhomme,	28 drivers licensed for 5+ years	in a simulator, 3 groups of drivers: familiar with FCW, unfamiliar with FCW and	• Collisions with FCW: familiar 0%, unfamiliar 20%, and control 40%

and Mas (2012)		had no contact with FCW (control group). FCW was above the dashboard and triggered a single visual and acoustic warning.	• Release of Gas pedal with FCW: familiar 100% and unfamiliar 82%. • Familiarization increases understanding of FCW. • Familiarization resulted in a lack of collisions, longer time headways, and shorter reaction times.
Muhrer, Reinprecht, and Vollrath (2012)	30 drivers (ages 20-40)	in a simulator, after 30 minutes of training, subjects followed a lead vehicle (50km/hr) in an urban area, with and without FCW+. The FCW+ warning displayed "Brake!" and "Braking Auto" icons with acoustic signals.	• 13 crashes without FCW+ 0 crashes with FCW+ • FCW+ reaction times were 88% shorter
Alves, Goncalves, Rossetti, Oliveira, and Olaverri-Monreal (2013)	22 drivers (ages 22-64)	in a simulator, car following at 50, 90, 120km/hr, HUD warning (2 versions) with or without an auditory warning.	• 91% found warnings with sound more adequate. • 86% found that the road safety marker icon was easier to understand than the traffic sign icon.

As shown in Table 12 (should this be table 11), providing a warning was consistently found to reduce response/reactions time, with more studies examining visual warnings than auditory warnings. Surprisingly, although a few individual studies examined specific characteristics such as sound intensity or frequency in a limited number of cases, there was not a systematic exploration of warning signal characteristics. In fact, some findings seemed counterintuitive, such as response times being less for sounds that were not as loud (possibly because the amount of disruptive startle was less). Furthermore, there were no consistent findings as to if unimodal or multimodal warnings led to shorter reaction/response times, in part because the outcome depended on the particular stimulus characteristics. Readers are encouraged to read Jeong and Green (2012) for additional details.

Table 12. Studies Including Response/Reaction Time as a Dependent Measure (Best Performance in Bold)

Study		Shorter Response/Reaction Time							
		No Warning	Unimodal			Multimodal			
			Auditory	Visual	Tactile	Auditory+ Visual	Auditory + Tactile	Visual + Tactile	Auditory + Visual + Tactile
1	Baldwin (2011) I, II		Ab (-2dB, **+4dB**, +10dB)						
3	Cheng et al. (2002)		Ab (fq-harmonics-repetition speed: 4000-1-10,**2000-2-10**,2000-2-2,2000-2-10)						
5	GM and Delphi-Delco (2002) I, II	X		Ab (1stage, 2stage), **I (looming,** looming+scale, scale**)**		Ab+I			Ab+I+V
6	Graham (1999)		Ab (tone 60.1dB), I (**horn 59.4dB**, tire-skid 62.8dB), W (speech 60.7dB)						
7	Gray (2011)	X	I (nonlooming: constant intensity, pulsed, ramped, **car horn**, **looming**: **veridical**, early, late)						
8	Ho et al. (2006)	X			**V (290Hz sinusodal)**				
9	Ho et al. (2007)	X	Ab (85dB)		V (290Hz sinusodal)		**Ab+V**		
10	Kiefer (2000)	X	**Ab**, W	Ab	V (Brake pulse)	**Ab+Ab**	Ab+V		

11	Kiefer et al. (2005) I, II, III	X				**Ab+I**			
13	Lee et al. (1997)	X				**Ab+Ab**			
14	Ljung et al. (2007) I					Ab+Ab, **Ab+Ab+ W**			Ab+Ab+V
14	Ljung et al. (2007) II	X				Ab+Ab, Ab+Ab+W			**Ab+Ab +V**
16	McGehee et al. (2002)	X	UNK (1.0s late, **1.5s early**)						
17	Rosario et al. (2010)			Ab	**V (2.5Hz, 5Hz, 10Hz)**				

Where:

Warning Modality	Warning Abbreviation
Auditory	Ab (Abstract = tone), I (Iconic sound), W (Word, spoken)
Visual	Ab (Abstract = light), I (Iconic), W (Word)
Vibration	V (Vibration)
Others	UNK (Unknown or unclear), X (No warning)

Table 13 shows studies examining the number of crashes reported in FCW experiments, not a commonly collected statistic because of the large number of crash provocative events required to have a meaningful number. The most common finding was that providing a warning reduced the number of crashes. Again, readers are encouraged to see Jeong and Green (2012) for additional information.

Table 13. Studies Including Number of Crashes as a Dependent Measure (Best Performance in Bold)

Study		Fewer Crashes							
		No Warning	Unimodal			Multimodal			
			Auditory	Visual	Tactile	Auditory+ Visual	Auditory + Tactile	Visual + Tactile	Auditory + Visual + Tactile
2	Baldwin and May (2011) I, II, III, IV, V	X				Ab + W (70dB+*Notice*, **85dB+*Notice***, 70dB+*Danger*, 85dB+*Danger*)			
13	Lee et al. (1997)	X				**Ab+Ab**			
15	May and Baldwin (2006)	X	Ab (1000Hz), **W (*Danger*)**						
16	McGehee et al. (2002)	X	UNK (1.0s late, **1.5s early**)						

Recommendations:

Five studies, one of which examined another 17 studies (covering 27 experiments), concerning forward collision warnings are described previously. Each of these studies used driving simulators or test vehicles to test the positive and negative effects of FCW. They tested different types of warning modalities (visual, auditory, or haptic) to conclude which design would be the most effective. However, determining which warning type or combination is most desired will require further analysis of the studies presented, in particular expanding the analysis began in Jeong and Green (2012).

LANE DEPARTURE WARNINGS

Lane departure warnings, depending on how they are implemented, either tell drivers they have left the lane of travel or are about to do so. The concern is that if a driver departs from a lane they could either sideswipe another vehicle in an adjacent lane or a roadside object.

Table 14 shows some of the more recent studies concerning lane departure warnings. Across the studies listed a wide variety of warnings have been examined – monaural and stereo beeps of specific frequencies, steering wheel vibration, images on head-up displays, simulated rumble strips, etc. As with other warning types, there has been no systematic exploration of warning characteristics.

Table 14. Some Relevant Studies of Lane Departure Warnings

Study	Subjects	Procedure	Findings
Suzuki, and Jansson (2003)	24 drivers, (ages 25-57, 12 subjects haptic warnings and 12 acoustic warnings.)	VTI driving simulator with the Volvo 850 cab; compared acoustic and haptic warnings: monaural beeps, stereo beeps, steering vibration and pulse-like steering torque. Subjects drove when not told of (unaware) and then told of warnings.	• Reaction Time: unaware and aware: Monaural beep sound- 1.19 s and 0.38 s; Stereo beep sound- 1.36 s and 0.38 s; Steering vibration- 0.52 s and 0.43 s; Pulse-like steering torque 0.72 s and 0.44 s. • Maximum Lateral Deviation: Unpredicted and predicted: Monaural beep sound- 1.75 m and 1.13 m; Stereo beep sound- 1.89 m and 1.10 m; Steering vibration- 1.36 m and 1.24 m; Pulse-like steering torque 1.83 m and 1.19 m. • Ssteering vibration was the most effective for warning drivers, especially when they did not know the meaning of the warnings.
Kozak, Pohl, Birk, Greenberg, Artz,	32 sleep deprived drivers,	Ford VIRTTEX moving base simulator with 2000 Volvo S80 cab; compared Head Up	• LDW reduced the reaction time from a mean of 1.17 s to 0.62 s. • Response time: Head Up

Blommer, Cathey, and Curry (2006)		Display (row of flashing red LEDs reflected on windshield), rumble strip sound (recordings from a vehicle driving over them at 65 mph), steering wheel vibration (15 HZ, 2 Nm, duration of 1.5 s) & steering wheel torque warnings. First 2 hours, yaw deviations caused lane departures. Last 20 min. drivers initiated lane departures.	Display 0.60 s, rumble strip sound 0.55 s, steering wheel vibration 0.46 s, steering wheel torque 1 s • LDW decreased lane excursions from a mean of 4.44 ft-s to 2.44 ft-s. • Steering wheel vibration decreased lane excursions to 1.39 ft-s. • Steering wheel vibration combined with steering wheel torque was most effective. • Drivers voted steering wheel vibration most helpful and acceptable.
LeBlanc, Sayer, Winkler, Ervin, Bogard, Devonshire, Mefford, Hagan, Bareket, Goodsell, and Gordon (2006)	78 drivers; 11 Nissan Altima 3.5SE's equipped with Road Departure Crash Warning (RDCW) and data acquisitio n system (used over 4 weeks – naturalisti c driving)	RDCW consisted of two warnings, lane drift warning and a curve-speed warning. The LDW and CSW used a combination of visual and haptic alerts for the lower level situations and visual and audible alerts for higher-level situations. The CSW and LDW shared a visual display space, motors in the driver's seat pan for haptic cues, and an audio system.	• 68% of drivers remained in lane when LDW occurred. • 18% increase of the use of turn signals on freeways and ramps when LDW provided. • Driver acceptance of LDW was generally positive • road types had a major influence on the CSW, see report for further information.
Green, Kang, Alter, Best, and Lin (2010)	24 drivers (8ages 18-30, 8 35-50, 8 >65),	~~2~~ Two 2009 Chrysler Town and Country Minivans (1 torque feedback and 1 vibration) driven on the expressway; steering wheel torque (3 Nm) or 2.4 kHz vibration provided (vibration was continuous or pulsed). Large and small icons	• 1459 lane departures occurred; 159 intentional • Driver response time: continuous- 0.96 s, pulse= 0.83 s, and torque=0.67 s. • Driver return time: continuous= 1.42 s, pulse= 1.07 s, and torque= 0.67 s. • Torque system was

		of a car and lanes were also presented in white and amber. Subjects asked to intentionally depart to get feedback.	preferred by half of drivers. • Driver wanted the intensity to be increased for torque warning. • Drivers preferred the large icon where only the lane color changed.
Burzio, Guidotti, Perboli, Settanni, Tadei, and Tesauri (2010) and Burzio, Buidotti, Perboli, Tadei, and Tesauri (2012)	570 drivers	Own vehicle = Lancia Delta (used over 9 months in Italy), Naturalistic driving (Italian FOT within euroFOT); effectiveness of a steering wheel torque warning; 280 had LDW, 290 did not (control group) Subjects complete 5 questionnaires that examine driver behavior, sensation, driving style, perception, safety, trust and effectiveness.	• Findings have yet to be located
Dass, Uyttendaele, and Terken (2013)	25 drivers (20 using simulator: 5 in truck on road)	In a simulator, subjects drove for 7 minutes with a haptic warning (in-seat) or an auditory warning (20 Hz) while performing a distracting task. On test track, truck drivers drove with 8 vibration motors (haptic only) in their seats and intentionally drifted from lane.	• Simulator: Outside lane 0.6% of time for no distraction, 2.4% for distraction. • For a number of departures, no difference between auditory and haptic warnings • Truck drivers compared auditory (from previous use) and haptic warning and stated, “It is something I wouldn’t switch off” and “[it’s] not that extreme.”

Recommendations:

Six studies regarding lane departure warnings are described previously. Each of these studies used various driving simulators or test vehicles to evaluate the different types of

warning modalities (visual, auditory, haptic or torque) to conclude which design would be the most adequate. According to the data above, haptic warnings seemed to be the most effective and accepted the most by drivers.

BLIND SPOT/LANE CHANGE/MERGE WARNINGS

A blind spot warning detects either that there is a vehicle in the area to the sides of the vehicle not visible by direct line of sight or a mirror, or a vehicle is about to enter that area because it is moving towards it quickly. A lane change warning indicates that a driver~~ing~~ is moving towards a location in another lane that is already occupied by another vehicle, typically in the blind spot. A merge warning indicates another vehicle is moving towards the subject's vehicle, usually from the blind spot. Sometimes the name side blind zone alert system (SZBA), side object detection system (SODS), and side collision avoidance system (SCAS) have been used to refer to systems for these purposes.

Lee (2004) reports that lane changes account for 4% to 10% of all crashes, and most drivers did not attempt a maneuver to avoid the crash, suggesting they were not aware of the hazard. Changing lanes requires more attention and has greater visual demand than normal highway driving due to the need to continually monitor areas around the vehicle (Lee 2004).

Table 15 summarizes several studies relating to lateral crash warnings. Note that the number examining alternative interface concepts is limited, in part because there have been a number of studies examining how drivers change lanes, which has provided useful insight into how lane change warning systems should be designed as well as the assessment measures. (See also Hetrick, 1997.)

Table 15. Selected Studies of Blind Spot/Lane Change/Merge Warnings

Study	Subjects	Procedure	Findings
Campbell, Hooey, Carney, Hanowksi, Gore, Kantowitz, and Mitchell (1996)	48 subjects (16 age =<25, 16 ages 26-54, 16 age >=55	STISIM driving simulator, warnings could be in exterior mirrors, near exterior mirrors, on dash, rear view mirror, the could be static, flash (4 Hz), move, or change size, many options for graphics (see Tables 16, 17), subjects asked questions about each (effective, communicates urgency, annoying,	• no driving performance or eye fixation data was collected – screening study • on dash location as most noticeable • considerable amount of data on driver responses to questions, but as there was not performance data (and limited experience), the results must be considered carefully

		etc.)	
Lee, Olsen, and Wierwille (2004) Also Olsen (2004)	16 commuters	instrumented vehicles each driven for 10 days, naturalistic driving, lane changes recorded (not a warning study)	• Characterizes normal lane changes Lane change duration ranges from 2.0 to 16.5 s, mean = 5.0-6.0 s • Turn signals are used infrequently in lane changes (44% of the time) Prior to lane changes, there was at least one 3 s long glance, often to front with transition probability to rear view mirror = 0.53, to left mirror = 0.47, to right mirror = 0.02 * Minimum acceptable gap of 40 ft frontward or rearward with a velocity <20 ft/s frontward or rearward and TTC of 4-6 s
Kiefer and Hankey (2008)	32 drivers (16 ages 40-50, 16 ages 60-70)	1999 GMC Suburban and 1998 Cadillac Seville fitted with LEDs in exterior mirrors – yellow if vehicle in blind spot, if turn signal activate when vehicle present, flashed red (4 Hz), told it was a ride study and blind zone system was difficult to turn off, 4 or 6 drives on expressway	• having system led to more glances to mirrors for lane changes, especially to left (e.g., glances to left mirror increase from 87 to 94% of changes) • system had no adverse effects on glance durations to mirrors or lateral acceleration
Guo, Wotring, and Antin (2010)	32 drivers (16 ages 16-21, 16 ages >=65)	Drove in NADS with proximity only warning (30 ft back, red triangle in mirror), proximity + fast approach, limited proximity (25 ft back, flashes LED), or non-planar mirror, changed lanes at various times	• no differences in number of crashes • non planar mirror had fewest number of near warnings (0) • many other measures were examined
Chun, Lee,	24 subjects	Video game based	• collision prevention rates were 43

Park, Seo, Choi, and Han (2013)	(12 ages 20-30) and (12 ages 50-60)	driving simulator (Irrlicht 3D engine), follow lead car with traffic that changed lanes, steering wheel or seat belt vibrated (120 Hz, 0.144 mm amplitude)	(steering wheel), 35 (seat belt) 29 (no warning), but seat belt-no warning difference was not statistically significant • mean minimum distances were 0.13 m (steering wheel), 0.09 m (seat belt), 0.08 m (no warning) • Steering wheel provided directional information whereas seat belt did not

Table 16. Warnings Presented in Campbell, Campbell, Gore, Kantowitz, and Mitchell, (1996)

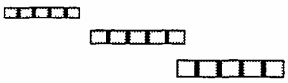
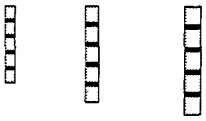
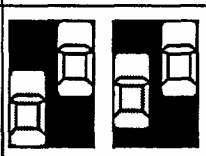
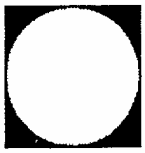
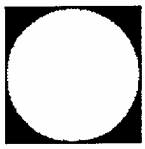
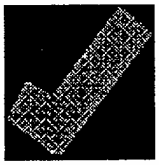
ALERT	STATIC/FLASHING	SIZE INCREASE	MOVING
Inverted Triangle			NA
Five Horizontal LEDs			NA
Five Vertical LED's			NA
Barber Pole	NA	NA	
Barber Pole and Caution	NA	NA	
Vehicle in Blind Spot		NA	
Prescriptive Arrow			NA
Descriptive Car Crash			NA
Tone 1 & Descriptive Car Crash		NA	NA
Muth Mirror		NA	NA

Table 17. Status Indicators Presented in Campbell, Campbell, Gore, Kantowitz, and Mitchell, (1996)

STATUS INDICATOR	STATIC/FLASHING
Green Circle	
Red Circle	
Green Circle + System OK	
Red Circle + System Malfunction	
Green Checkmark	
Red X	

Of these studies, Campbell, Hooey, Carney, Hanowksi, Gore, Kantowitz, and Mitchell (1996) provide the most amount of data and it is certainly worth examining for additional information. However, as those authors note, their research was a screening study, and in fact, it relied primarily on impression from viewing/listening to the driver interface, not performance data that would provide information on the number of crashes, minimum gaps during encounters, or other statistics. Accordingly, the evidence as to which subjects thought would be best should be viewed with great caution.

Recommendations

The current trend for these warning systems is to either illuminate an LED in or near the relevant mirror, or vibrate the seat, or both. There may also be an accompanying sound if a crash is imminent. However, optimization of the stimuli within modalities has not been done so that a careful between-modality comparison can be made. Given the limited scope of this review, what can be recommended is limited as well.

If a system is developed to accurately predict driver intention to change lanes, such as using eye glance statistics combined with turn signal usage, an LCW system has the potential to greatly reduce crashes when changing lanes and merging in to traffic.

BACKING WARNINGS

Backing warnings are warning systems that use ultrasonic sensors and/or rear-view cameras to provide drivers with information about obstructions in the backing path to help prevent crashes. Studies on backing warnings examine the process of the task (back) and the interplay between the task and the format of the warning to a greater degree than warnings for other tasks (e.g., driving forward) (Table 18).

Table 18. Selected Studies of Backing Warnings

Study	Subjects	Procedure	Findings
Harpster, Huey, and Lerner (1996) See Lerner, Harpster, Huey, and Steinberg, (1997) for more information	21 (12 young (mean = 23), 9 elderly (mean = 73)	subject drove their own vehicles performing 6 backing maneuvers on a course (extended curve backing, parallel parking, back out of stall and angled parking, back to a wall, back into stall); Note: No rear cameras at this time.	• Looking over right shoulder ≈50% of time when backing • Glances to 3 mirrors were 37% of time for older drivers, 15% for younger • Maximum backing speed was 5 mph except for extended backing (often >10 mph) • In example given, TTC decreased exponentially to 5 s and remained stable 4 s after backing began • Drivers typically traveled <3 ft in first backing s, 8 ft after 2 s
Alter and Green (2010)	12 licensed drivers, 6 young (20-33), 6 old (65-86), all groups split evenly with men and women, limited experience with backing systems	2009 Infiniti FX-50S used in a parking lot with 3 blocks: no backup warning system, backup system w/ warning tone (standard on car), and Back-Up Collision Prevention (BCP). Subjects went through backing trials with random obstructions	• Subjects shifted to reverse, removed their foot from brake, young group more variable braking • Backup speeds between 0 and 1 m/s, younger group had higher mean speed • gap (ft) between obstacles and car = 3.9 + 0.07 x (estimated distance in ft) • With back up collision prevention (BCP, crossing traffic warning), stopping distance for crossing vehicles was greater by 8 ft • Time for backup maneuvers did not vary based on BCP implementation, but varied

			greatly based on distance of approaching vehicle
Hurwitz, Pradhan et al. (2010)	46 licensed drivers, ages 21-35	Various backing maneuvers in a car with an audible alert and a rear camera, backing distance varied, eye fixations recorded	• Only 20% of drivers look at rear camera before backing • 88% of the above group did not crash • 46% of the group who did not look at the camera initially, looked after sensor warned driver of imminent danger • Initial camera glances decrease over time
Kim, Rauschen-berger et al. (2012) Also Heckman et al. (2012)	77 licensed drivers (ages 18 – 68) without experience with backup system	2011 Ford Edge, eye tracker, not display vs. 3.3 in mirror display vs. small (4.1 in) IP display vs large (7.9 in) IP display. (tasks included back and pull into stall, back out of stall, parallel park, back out of driveway	• Obstacle avoided: 18% no display, 35% large display, 48% mirror display, 52% small display • Response times when obstacle avoided were: 1.25 s mirror display, 2.76 s large display, 2.96 s small display
Kochhar, Talamonti, and Tijerina (2012) See also Kochhar, Talamonti, and Tijerina (2013)	2 Studies: 44 Ford employees (ages 24-62) and 48 volunteers, (15-53)	Back modified 2011 Lincoln MKT out of space between 2 parked vehicles and vehicle automatically brakes, 1 trial/subject; Study #1 nothing was behind, #2 cone was behind the car when brakes activated, In both cases warning text was shown (e.g., check behind)	• In both studies, 98-100% of participants had their foot on the brake within 0.8s of brake activation • In #1, 32% looked at rear camera image when brakes activated, 46% looked at mirrors • 32% had foot on accelerator when brakes released, 66% still had foot on brakes • In #2, 50% looked at rear camera image when brakes activated, 40% looked at mirrors, 10% over shoulder • By brake release (3 s after braking), <u>all</u> had looked at rear camera image, no one ran the cone (study 2) over
Kidd, Hagoski,	111 drivers (ages 18-58) split by	15 with no tech, 32 in audible sensor	• % surprise trials object struck, stationary/moving:

Tucker, and Chiang (2014)	test condition	condition, 32 in camera condition, 31 with both; backing tests with moving and stationary object detection, occlusion test of distraction followed by surprise trial of target while backing	no technology = 100/15, sensor 95/38, camera 55/14, camera + sensor 75/8 -> favors camera and camera + sensor • object in shade was always struck

Those interested in warning timing issues should see Muttart, Hurwitz, Pradhan, Fisher, and Knodler (2011).

Recommendations

The core requirements are described in the recent modifications to Federal Motor Vehicle Safety Standard 111 (U.S. Department of Transportation, 2014). As of 2016, all light vehicles must have a camera system to a show a "visual image" of shown in Figure 2. The standard provides addition details regarding the test procedure. Manufacturers may provide other warnings (e.g., auditory) as well.

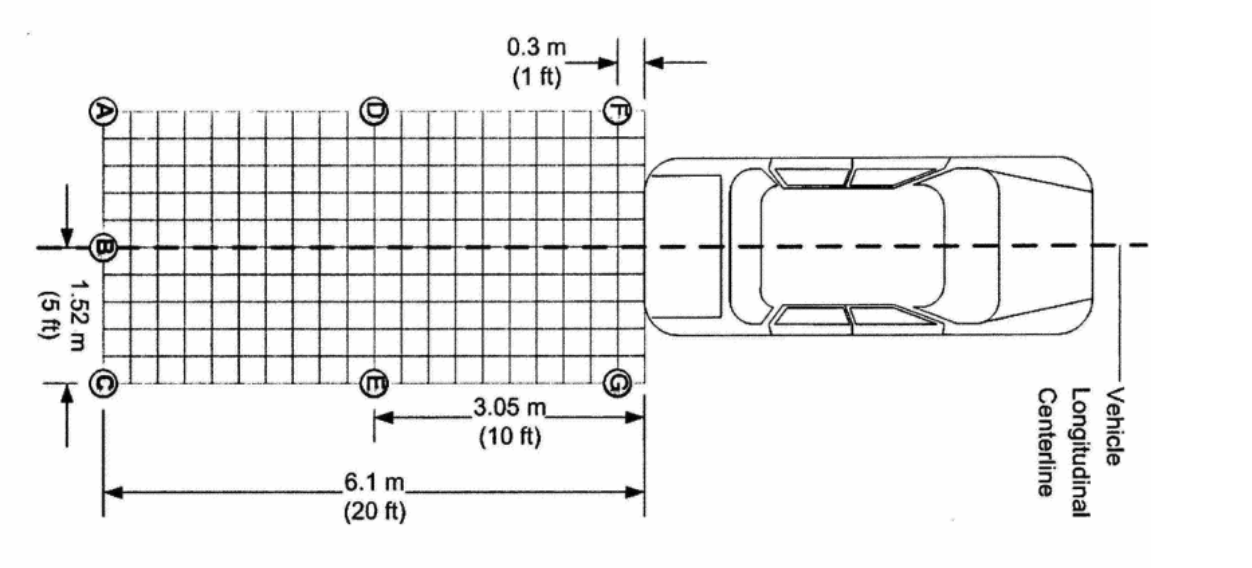


Figure 2. Required Area Behind the Rear Bumper.

The NHTSA requirement is well supported by the research, with the value of an auditory supplement being task specific. The benefits of supplement automatic braking, a topic beyond the scope here, are apparent (Alter and Green, 2010). What markings should appear on a display has not been given much attention.

INTERSECTION WARNINGS

One of the more comprehensive and recent reviews for traffic signal warnings is Green, Demeniuk, and Jih (2008). That report found that red-light running occurred on a wide range of roads (2-, 3-, and 4-lane roads, each about 20% each), with being late, trying to beat the signal, and frustration with traffic as being common reasons. Crash frequency increased roughly with the square root of traffic volume.

That review led to the development of the warning display shown in Figure 3. In brief, the traffic signal showed the current phase and the digit indicated the time to the phase change (in seconds). The red LED on the right blinked if a traffic signal violation was expected. The presence of the display reduced the number of yellow violations by one half, on average, and the number of red violations to almost zero when not texting, and half while texting.

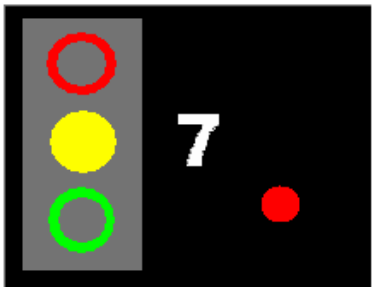


Figure 3. Stop-signal Violation Display Evaluated by Green, Schweitzer, and Alter (2008).

For stop sign violations, the focus has been on warning the driver of a vehicle if they are going to run a stop sign. Lee, Knipling, DeHart, Perez, Hollbrook, Brown, Stone, and Olsen (2004) provide a thorough overview of the literature and the functional performance requirements for a system. In a subsequent study, Neale, Perez, Lee, and Doerzaph (2007) describe an experiment in which subjects approached an intersection, and at random points in time, the vision was occluded for 2 seconds, after a warning was presented. A number of those warnings were related to the infrastructure. As shown in Table 20, brake pulses, of which they tested many combinations, were most effective.

Table 20. Effectiveness of Stop Sign Warnings (Percentages)

Condition	Successful Stops	Successful Over Baseline	Nuisance Warnings
Tone (2500 Hz, 4 times) + stop sign visual	33	14-33	Low (<3)
Verbal “STOP” + stop sign visual	81	60-81	Low (<3)
1 600 ms brake pulse, 0.3 g	100	69	High (~50)

3 600 ms brake pulses, 0.3 g	100	81	High (~50)
3 160 ms brake pulses, 0.3 g	100	81	High (~50)
continuous brake pulse, 0.3 g	100	81	High (~50)
Verbal “Red light” + soft braking, 0.3 g	???	???	High (~50)
Comparison – full braking, 0.39 g	100	100	Very low (<0.2)
Hypothetical case – verbal “red light” + panic brake assist (0.5g)	100	100	Low (<0.3)

See Neale, Perez, Lee, and Doerzaph (2007) for details.

However, the intersection problem is much larger than this as drivers need to be warned when they are going to run stops signs, and furthermore, when others may do so as well.

Research on in-vehicle warnings for stop sign violations has been limited (. For example, Pierowicz, Jocoy, Lloyd, Bittner, and Pirson, 2000). Furthermore, for additional specifications for warning system characteristics relevant to this topic, see Lee, Knipling, DeHart, Perez, Hollbrook, Brown, Stone, and Olsen (2004).

Recommendation:

The review of intersection warnings, because of the scope, most likely misses a number of key studies on this topic. Of the studies examined, there is not clear favored warning or warning set. There have been successful uses of visual displays with tones, as well as brake pulses. However, the warning that is most effective may depend on what the warning is communicating – that the driver is violating a stop sign or traffic signal, or that another driver is doing such. One of the key points emerging from this section is then even if a particular warning type is selected, there is considerable research needed to optimize it. For example, as was just described, there have been studies examining 1 and 3 brake pulses for intersection warnings, but the outcome for 2 brake pulses is unknown. Furthermore, all of the data is for pulses of 0.3 g.

In other sections, the possibility of a seat belt warning (tightening the pre-tensioner) is mentioned. That interesting warning has not been explored for this purpose, but should be.

FIRE WARNINGS

As was noted earlier, fires are associated with crash fatalities, although the percentage is not large, and the fire is invariably due to a collision. Although this report does not have statistical data to offer, the attention given to motor vehicle crash fires appears to be well out of proportion to their frequency. Attention given fires associated with the Ford Pinto and more recently the Ford Crown Victoria are ample indications of such (Dowie, 1977; Schwarz, 1990; Gioia, 1992; Arndt, 2004). Accordingly, some thought has been given to automotive fire suppression systems (Dierker, Thompson and Wieranga, 2005) and there are numerous patents for such. However, not much attention is given to warnings, the focus of this section. Before dismissing fire suppression systems for motor vehicles, keep in mind that if offered, there is potential customer demand. However, there may be weight penalties that make achieving fuel economy standards more difficult and without extremely high reliability, there are likely to be litigation issues.

In terms of fire warnings, the focus has been almost exclusively on buildings, with recent work on effectiveness concerning auditory alarms, specifically, how well alarms wake up people that are sleeping (Huey, Buckley, and Lerner, 1994; Nober, Peirce, Well, Johnson, and Clifton, 1980; Ahrens, 2008; Grant, 2008). Home fire alarms tend to be high-pitched tones at about 4000 Hz, with other tones at low frequencies. The ISO and NFPA specifications (International Standards Organization, 1987; National Fire Protection Association, 2013), often used in commercial settings, appears to support what is known as a T-3 signal – bursts of 3 sounds of 0.5 s duration separated by 0.5 s with 1.5 s between bursts. There are no specifications for the frequency, in part because there are large differences alarms used for that purpose (file:///Users/paulgreen/Documents/IMO-ISO8201-Ljud-Offshore.pdf). In buildings, one is concerned with where alarms are located, the construction of the building, and therefore if they can be heard. That is not the case in a motor vehicle.

Given that, the research makes are good case for having “Fire” spoken in a male voice as the warning. When heard, there is no doubt what it means, at least to those who know the English language. In a number of western European languages, the word used has some similarities (fuego in Spanish, feuer in German, feu in French).

Recommendation:

Research to examine the use of verbal warnings to alert drivers of fire should be supported.

DRIVING TOO FAST WARNINGS

Given the limited project resources, the decision was made to focus this section on a particular solution –-- active pedals – to reduce speeding in general and driving too fast in particular situations.

For those unfamiliar with them, active pedals, actually an active accelerator, pushes back on the driver when an undesired behavior occurs. Pedal forces have been used to encourage greater following distances, more economical driving, and to reduce speed, in particular when drivers exceed speed limits. Typically, when the driver exceeds the speed limit, they pedal becomes significantly more difficult to push, much more difficult per percent of pedal travel than below the speed limit.

Varhelyi and his colleagues have dominated recent research on active pedals though others have made significant contributions (Table 21). Speed driven has been the primary dependent measure, and, in general, they consistently report that people drove more slowly when active pedals were provided, typically by about 3 km/hr at high speeds.

Unfortunately, details of the pedal characteristics are not given in many of these studies, making implementation more difficult. For example, Varhelyi, Hjalmdahl, Hyden, and Draskoczy (2004), page 729 state, "The interface … consists of … an active accelerator pedal, which exerts a counterforce at speeds over the speed limit. In order to exceed the speed limit, the pedal must be pressed approximately three to five times harder than normally." In contrast, Jamson, Hibberd, and Merat (2013), manipulated pedal characteristics and provide force travel diagrams. Based on their research, when subjects drive in an undesired manner, a step change in pedal force leads is more likely to get subjects to drive in the desired manner than a linear increase in pedal stiffness. Exploration of additional levels of step changes is desired along with exploring combined force – stiffness changes.

Table 21. Selected Papers on Haptic Pedals

Study	Subjects	Procedure	Findings
Varhelyi and Makinen (2001)	20-24 drivers in 3 countries (Sweden, Netherlands, Spain)	drive over a variety of urban and rural roads, 1 test car	• for free (not following) driving, pedal feedback led to reductions in speed - most pronounced for speed limits less than 70 km/hr • greatest reductions were for speed of 40 and 60 km/hr, but oddly, much less for 50 km/hr • some shorter time gaps at 70-90 km/hr (less safe) • improvements in approach to intersections, roundabouts, and

			curves
Hjalmdal and Varhelyi (2004)	28 drivers	33 km route - variety of roads in Lund, Sweden, modified 99 Toyota Corolla	• overall increase in mean time gap with haptic pedal (1.72 to 1.89 s), with notable change for gaps of 1 to 1.6 s (as safety benefit)
Varhelyi, Hjalmdahl, Hyden, and Draskoczy (2004)	284 vehicles in Lund, Sweden	own vehicle, driving in test area, 5-11 months	• significant compliance with speed limits and shift in distribution to lower speeds, though not for every test section and the amount depended upon if the current speed was over the speed limit • mean decrease was 3.7 km/hr for 70 km/hr dual carriageway, 3.5 km/hr for 50 km/hr dual carriageway, 2.7 km/hr for single carriageway, and <1 km/hr for streets (30-50 km/hr)
Adell and Varhelyi (2008)	281 drivers in Sweden	naturalistic driving in a test area for 6-12 months, own vehicle	• drivers were satisfied with the system and rated it positively on a number of dimensions
Adell, Varhelyi and Hjalmadahl (2008)	28 drivers in Hungary and Spain	naturalistic driving for 4 months, active pedal and beep and flashing light (when speeding), own vehicle	• auditory warnings (beeps) reduced the mean speed by 2.8 km/hr and the active pedal by 3.9 km/hr • 85 % reductions were 7.2 and 3.6 mi/hr. • more drivers wanted to keep the auditory warnings even though it showed lower satisfaction ratings than the active pedal
Jamson, Hibberd, and Merat (2013)	20 drivers in UK	U of Leeds driving simulator, cruise (built-up area, 40 m/hr), accelerate (rural, 60 m/hr), cruise	• drivers were best guided towards a most fuel efficient gas pedal position by force feedback (where a driver feels a step change in gas pedal force, approx. 25 to 65N) as opposed to stiffness feedback (where a driver feels a changing gas pedal firmness, for 0.2N per % travel to 1.45N or 2.9N) • see the report for the force levels

Thus, there appear to be significant benefits to haptic pedals to reduce speeding. However, there may be differences between American and European drivers in their acceptance of technology that recommends how fast they should drive, so the provision

of haptic pedal feedback may need to be examined in the U.S. Almost all of the studies just cited were conducted in Europe. Furthermore than focus on general warnings for speeding, an initial application that may be better received is one that indicates when driving is too fast for the conditions. Such ~~as~~ an ~~assessment~~ application will require an assessment of road surface condition and visibility, and possibly other characteristics.

Due to lack of time, this review has not considered haptic brake characteristics (e.g., pulsing brakes as a warning). For a detailed evaluation of haptic brake characteristics, see Tijerina, Johnson, Parmer, Pham, Winterbottom, and Barickman (2000).

HORNS AS WARNING DEVICES

The traditional approach to warning systems is to consider think about what the vehicle alone can present to the driver of that vehicle – visually, auditorally, and haptically. With connected vehicles, thought is also being given as to how vehicles can communicate with each other, and then with the drivers of those vehicles.

However, there is a driver to driver communication mechanism that is not given much attention in the crash literature – the horn, the first collision warning. In part, that is because horn use not coded on crash reports. Every motor vehicle has a horn, and to some extent the sound of the horn suggests the size of the vehicle. High pitch sounds usually come from compact cars, lower frequency sounds come from large cars, and deep sounds, usually from air horns, come from large trucks. See SAE standard J377:2007 (Society of Automotive Engineers, 2007) for details.

People sound their horns for a variety of reasons, but two are safety related. First, the honking driver is trying to draw attention to themselves at an intersection, during a merge, when backing, or in other maneuvers. The message could be "look out for me," or "get out of my way," or something else. This message could be intended for another driver, a pedestrian, or even an animal. In that case, identifying who is honking quickly and accurately is important. Currently, drivers listen for the sound, use the unwritten convention linking vehicle size to sound to find the honking vehicle, and respond accordingly. Usually 2 honks are required. The first alerts the driver to pay attention to something. The second helps drivers locate the honking vehicle. Automatically flashing the lights could help drivers identify who is honking at them.

A second use of horns is to inform other drivers to (1) watch out for something else other than the driver who is honking, (2) raise that driver's alertness if they are distracted, inattentive, drowsy, or asleep, and (3) to get them to move when a traffic signal changes (which is a specific instance of inattentiveness) or in other situations. Currently, the same signal is used for all of these purposes. However, in contrast to the first case, the emphasis is on more focus on the vehicle being warned, and so knowing who is honking is less useful, and flashing the lights in all cases could be misleading.

There is a convention, a language, as to how horns are used. Generally, the longer the horn is sounded, the more urgent the situation. Drivers may also operate the horn repeatedly, with the first time being so drivers are alerted and the repeated presses to either convey urgency or allow the other drivers to identify the honking party. This may be a courteous alternative to a continuous honk. Overlayed on top of this are major differences between countries as to how often horns are used and how they are used as well as individual differences between drivers often related to their aggressiveness (Forgas, 1976;Turner, Layton, and Simons, 1975; Halderman and Jackson, 1979; Bradley, 1991).

One of the difficulties with using the horn as a signaling device is that drivers often do not respond to situations by honking very quickly, and drivers rarely brake and honk at

the same time, and because of response conflicts, find it very difficult to steer and honk at the same time.

Recommendations

At this point, the authors do not have an specific recommendations about how to utilize horns more effectively as a warning device other than that consider flashing the lights in some circumstances when the horn is sounded. One way to accomplish this would be to have 2 contact areas on the steering wheel for the horn, 1 that just sounded the horn, and 1 that sounded the horn and flashed the lights. Given that horn control design convention is well established, how well this suggestion would be received and how useful this addition feature will be in practice is unknown.

Another ~~possibly~~ possibility is to sound the horn automatically (or provide some other external sound) when a warning system reaches a critical point (such as when a crash mitigation braking system begins to slow the vehicle). Currently, drivers rely on the sound of squealing tires.

WARNINGS SYSTEM FRAMEWORK

The purpose of the previous section is to characterize the current situation with regards to warnings – some of the guidelines that exist and research findings. Certainly, the guidelines cited here are supplemented by SAE and ISO standards, documents that have been reviewed in a previous report to the sponsor. For the sake of economy, that report is not summarized here. In addition, of interest is what warnings manufacturers are using now, also described in a previous report to the sponsor (Lin and Green, 2013).

What then is the current situation with regard to warnings?

1. It is apparent that some warnings and crash avoidance systems are beneficial in reducing the number of crashes (Insurance Institute for Highway Safety, 2010)

2. The focus to date has been on the modality of the warning, an important characteristic. However, there has been insufficient attention to the evaluation of warnings within particular modalities. In a typical experiment, a particular light is compared with a particular tone. However, what remains unknown is how changing the intensity, location, repetition characteristics of either stimulus, the color of the light, or the frequency of the tone would affect the outcome of the experiment. As shown in (Jeong and Green, 2012), to the uninformed, the combinations selected seem random. There needs to be a more systematic exploration of warning characteristics, and that need was the motivation for the ongoing evaluation supported as part of this project (Lin, Kang, and Green, 2014).

3. The most important purpose of a warning is to alert the driver of something of which they are unaware, orient them to its location, and, if needed, tell them what to do. Much more needs to be done to determine when the driver is unaware of hazard and when directing them to look towards a location is useful. That will require low cost methods to determine where drivers are looking, which is becoming a reality. However, even if the driver is looking at something, one cannot be 100% sure they are aware of it – the “looked but did not see” problem. Nonetheless, integration of eye fixation/head position monitoring systems into warning systems needs to be considered.

4. Awareness, coupled with the consequences, needs further consideration. For example, drivers tend control lateral position in a manner that is responsive to road geometry and traffic. If the lanes are narrow or traffic is greater, then standard deviation of lane position is less. In contrast, if there is no traffic, and the driver is in the middle of 3 lanes in their direction, then lane departures are of less consequence, and the rules that trigger a departure should be more liberal (e.g., no triggering on approach) so as not to annoy drivers.

5. There has been considerable concern expressed about how to deal with multiple warnings. As was found in the IVBSS driving simulator studies, it was extremely

difficult to cause 2 warnings to occur at the same time, even if one intentional created scenarios for such. Often, some event occurred that triggered FCW, the subject maneuvered, and LDW triggered. The LDW was superfluous because the driver was aware of the situation and they knowing caused the LDW to trigger.

Multiple warnings are an issue for parking (both entering and ~~entering~~exiting) where restricted visibility and limited space, as well as the maneuvering situation make it difficult for the driver to have perfect knowledge of potential contacts around the vehicle. This is particularly likely when the driver is backing and turning at the same time, where either the front or back of the vehicle could strike something, but can occur when the vehicle is moving forward, especially if on a curved path. Thus, the parking and backing situation need attention. In other cases, only presenting the first warning, except when FCW needs to override, is a sensible strategy.

6. There is a desire to use tones as an alert. Some thought has been given to considering which frequencies and intensities are likely to be heard, ~~and~~ but more work needs to be done. ~~However, F~~of ~~f~~or the most part, regardless of the frequency, it is just a matter of making the tone loud enough. However, there is no stereotype for which frequency of a tone is an automotive warning as opposed to indicating something else, and no apparent consistency between vehicles.

   One potential solution is to not use pure tones, but combinations of sounds that "sound bad" when presented together, in brief, nonharmonic combinations.

7. In designing warning systems, what is known as the 2-stage fallacy exists, with the assumption being that a warning is either off or on, and if the situation becomes more ~~several~~severe, then a warning of some other modality is needed. The selection of the threshold for the second (imminent warning) level often leads to debate. An alternative strategy is to use a graded warning, such as for auditory back up warnings, where tones beep more rapidly as the threat becomes greater. Repetition of visual and haptic warnings can be used in the same manner, as can warning intensity differences, but they are less noticeable over a short period of time than repetition. The key point is to use repetition to code urgency.

8. From an academic perspective, except for the ACAT project, the research on automotive warnings is very weak (Green, 2014). There are no pre-experiment predictions of outcomes, and models and theories are not used to make quantitative predictions of warning detection, response, or effectiveness. This is not true of the related ongoing assessment of warning detection (Lin, Kang, and Green, 2014).

9. Seat belt pretensioning can be a very noticeable warning, though its desired characteristics --final tension desired, rate of onset, consideration of out of position occupants – have not received attention. Further exploration is needed.

To the authors, this information suggests an integrated warning system that could function as follows. Keep in mind that this suggestion is a based on the limited review

conducted and the first author's knowledge of the topic. A more detailed review could lead to an alternative proposal.

1. If a hazard is detected, a sound is presented that is not a pure tone to alert the driver to look for a hazard. The triggering of this first warning depends upon if the driver is looking towards the hazard or not. If there are 2 hazards, then the sound would alternate between 2 sounds, but only when backing.

2. At the same time, an LED is illuminated in the direction of the hazard. How this will be accomplished for hazards to the rear has not been determined. Also to be determined is, if and how hazards that are not visible should be coded, and what the relationship is between the difference in visual angle of the LED and hazard, and the time to find the hazard.

3. As the hazard increases, the repetition rate of the sound increases.

4. When a crash becomes imminent, the seat belt pre-tensions.

5. For backing up, a camera image is provided. However, other enhancements are needed to encourage drivers to look outside the vehicle when backing.

6. At no time should an explanation for the warning be provided on the center console ~~on~~ or in the speedometer/tachometer cluster, as the explanation draws the driver's attention away from the external environment. If needed, the explanation should be in a mirror or on a HUD or some place at which or nearby where the driver is looking.

7. The growing evidence, as one would suspect, is that more substantial benefits accrue when crash warning systems are coupled with systems that have some control authority – forward crash warning with crash avoidance braking, lane departure warning with keeping assistance, and backing warning with cross traffic alert. Thus, feedback should be provided via the control the driver is operating. If the driver is driving too fast for conditions, then either force feedback and/or pedal vibration should be provided. If a merge or lane change puts the driver on a collision course, especially if the turn signal is not operated, then the steering wheel torque required should be greater. Studies in the literature have found that vibrating the steering wheel can also be an effective cue. To be consistent, that would suggest the pedal should also vibrate, which has not been examined.

8. The next generation of warning systems may be able to take advantage of augmented reality warnings, for example, using the entire windshield as a display. The beginnings of those warnings are being developed as part of an ongoing project at the University of Michigan supported by NSF.

REFERENCES

Adell, E. and Varhelyi, A. (2008). Driver Comprehension and Acceptance of the Active Accelerator Pedal after Long-Term Use, Transportation Research Part F, 11, 37-51.

Adell, E., Varhelyi, A., and Hjalmdahl, M. (2008). Auditory and Haptic Systems for In-Car Speed Management – A Comparative Real Life Study, Transportation Research Part F, 11, 225-258.

Alter, M. and Green, P. (2010). Driver Use of a Backup Warning System That Automatically Brakes (technical report UMTRI-2010-13), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Alves P., Goncalves J., Rossetti R., Oliveira E. and Olaverri-Monreal C. (2013). Forward Collision Warning Systems Using Heads-Up Displays: Testing Usability of Two New Metaphors, 2013 IEEE Intelligent Vehicles Symposium Workshops, 5, 1-6.

Arndt, M. W. (2004). Safety Standard's Failure to Reveal Defects In Police Vehicle's Fuel System Crashworthiness, Proceedings of the ICRASH 2004 Conference, San Francisco, CA.

Ahrens, M. (2008). Home Smoke Alarms: The Data as Context for Decision, Fire Technology, 44, 313-327.

Bradley, D.R. (1991). Anatomy of a SATASIM Simulation: The Doob and Gross Horn-Honking Study, Behavior Research Methods, Instruments, and Computers, 23(2), 190-207.

Bruck, D. and Thomas, I. (2008). Comparison of the Effectiveness of Different Fire Notification Signals in Sleeping Adults, Fire Technology, 44, 1-38.

Burzio, G., Guidotti, L., Perboli, G., Settanni, M., Tadei, R., and Tesauri, F. (2010). Investigating the Impact of a Lane Departure Warning System in Real Driving Conditions: a Subjective Field Operational Test, European Conference on Human Centred Design for Intelligent Transport Systems.

Burzio, G., Guidotti, L., Perboli, G., Tadei, R., and Tesauri, F. (2012). Results and lessons learned of a subjective field operational test on the lane departure warning function. Procedia-Social and Behavioral Sciences, 48, 1356-1365.

Campbell, J. L., Hooey, B.L., Carney, C., Hanowski, R.J., Gore, B.F., Kantowitz, B. H., and Mitchell, E. (1996). Investigation of Alternative Displays for Side Collision Avoidance Systems (technical report DOT HS 808 579), Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Campbell, J.L., Richard, C. M., Brown, J. L., and McCallum, M. (2007). Crash Warning System Interfaces: Human Factors Insights and Lessons learned (Technical Report DOT HS-810 697), Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Campbell, K. L., Wolfe, A. C., Blower, D. F., Waller, P. F., Massie, D. L., and Ridella, S. (1990). Accident Data Analysis in Support of Collision Avoidance Technologies, Final Report (technical report UMTRI-90-31), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Chun J., Han S., Park G., Seo J., Lee I. and Choi S. (2012). Evaluation of Vibrotactile Feedback For Forward Collision Warning on the Steering Wheel and Seatbelt, International Journal of Industrial Ergonomics, 42, 443-448.

Chun, J., Lee, I., Park, G., Seo, J., Choi, S., and Han, S. H. (2013). Efficacy of Haptic Blind Spot Warnings Applied through a Steering Wheel or a Seatbelt, Transportation Research Part F: Traffic Psychology and ~~Behaviour~~Behavior, 21, 231-241.

Damouth, D. and Green, P. (1997). Influence of Warning Message Content on Message Understandability and When Drivers Respond (technical report UMTRI-97-22), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Dass Jr, D. E., Uyttendaele, A., & Terken, J. (2013, October). Haptic In-Seat Feedback for Lane Departure Warning, Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, 258-261.

Davis, T. C., Wolf, M. S., Bass, P. F., Thompson, J. A., Tilson, H. H., Neuberger, M., and Parker, R. M. (2006). Literacy and Misunderstanding Prescription Drug Labels. Annals of Internal Medicine, 145(12), 887-894.

Dierker, J. B., Thompson, R. H., Wierenga, P. H., & Schneider, M. A. (2005). Development of Ford Fire Suppression System (SAE paper 2005-01-1791), Warrendale, PA: Society of Automotive Engineers.

Dowie, M. (1977). Pinto Madness, Mother Jones, 2(8), 1977.

Edworthy, J. (Ed.). (1996). Warning Design: A Research Prospective, Boca Raton, FL: CRC Press.

Forgas, J.P. (1976). An Unobtrusive Study of Reactions to National Stereotypes in Four European Countries, Journal of Social Psychology, 99, 37-42.

Frantz, J. P., and Rhoades, T. P. (1993). A Task-Analytic Approach to the Temporal and Spatial Placement of Product Warnings~~.~~, Human Factors, 35(4), 719-730.

General Motors (1997). 44-Crashes (version 3.0), General Motors Corporation, NAO

Engineering, Safety & Restraints Center, Crash Avoidance Department, January 1997.

Gioia, D. A. (1992). Pinto Fires and Personal Ethics: A Script Analysis of Missed Opportunities, Journal of Business Ethics, 11(5-6), 379-389.

Grant, C.C. (2008). Intelligibility of Fire Alarm and Emergency Communication System (final report), Quincy, MA: The Fire Protection Research Foundation.

Green, P.A. (2014). Doing Better Driving Research: Suggestions from a Reviewer, European Conference on Human Centred Design for Intelligent Transport Systems-2014, Vienna, Austria.

Green, P., Demeniuk, C., and Jih, S. (2008). In-Vehicle Traffic Signal Violation Warnings: A Review of the Human Factors Literature (technical report UMTRI-2008-10), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Green, P., Kang, T-P., Alter, M., Best, A., and Lin, B. (2010). Driver Performance with and Preferences for Lane Departure Warning System Feedback: Steering Wheel Torque vs. Vibration (technical report UMTRI-2010-11), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Green, P., Schweitzer, J., Alter, M., and Demeniuk, C. (2008). Traffic Signal Violation Warnings: Driver Interface Development and an Initial Driving Simulator Evaluation (technical report UMTRI-2008-11), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Green, P.A., Sullivan, J.M., Tsimhoni, O., Oberhotzer, J., Buonorasa, M.L., Devonshire, J., Schweitzer, J., Baragar, E., and Sayer, J.R. (2008). Integrated Vehicle-Based Safety Systems (IVBSS): Human Factors and Driver-Vehicle Interface Summary Report (technical Report UMTRI-2007-43), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Guo, F., Wotring, B.M., and Antin, J.F. (2010). Evaluation of Lane Change Collision Avoidance Systems Using the National Advanced Driving Simulator (technical report DOT HS 811 332), U.S. Department of Transportation, National Highway Traffic Safety Administration.

Halderman, B.L. and Jackson, T.T. (1979). Naturalistic Study of Aggression: Aggressive Stimuli and Horn Honking: A Replication, Psychological Reports, 45, 880-882.

Harpster, J., Huey, R., and Lerner, N. (1996). Field Measurement of Naturalistic Backing Behavior., Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Santa Monica, CA: Human Factors and Ergonomics Society, 891-895.

Heckman, G. M., Kim, R. S., Lin, S., Rauschenberger, R., Young, D. E., and Lange, R. (2012). Drivers' Visual Behavior During Backing Tasks: Factors Affecting the Use of Rearview Camera Displays., Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Santa Monica, CA: Human Factors and Ergonomics Society, 2236-2240.

Hetrick, S. (1997). Examination of Driver Lane Change Behavior and the Potential Effectiveness of Warning Onset Rules for Lane Change or "Side" Crash Avoidance Systems (Doctoral dissertation), Blacksburg, VA: Virginia Polytechnic Institute & State University).

Hjalmdahl, M. and Varhelyi, A. (2004). Speed Regulation by In-Car Active Accelerator Pedal: Effects on Driver Behaviour, Transportation Research Part F, 7, 77-94.

Huey, R.W., Buckley, D.S., and Lerner, N.D. (1994). Audible Performance of Smoke Alarm Sounds, Proceedings of the Human Factors and Ergonomics Society Annual Meeting 1994, Santa Monica, CA: Human Factors and Ergonomics Society, 147-151.

Hurwitz, D. S., Pradhan, A., Fisher, D. L., Knodler, M. A., Muttart, J. W., Menon, R., and Meissner, U. (2010). Backing Collisions: A Study of Drivers' Eye and Backing Behaviour Using Combined Rear-view Camera and Sensor Systems, Injury Prevention, 16(2), 79-84.

Insurance Institute for Highway Safety (2010). New Estimates for Benefits of Crash Avoidance Features on Passenger Cars, Status Report, 45(5), http://www.iihs.org/iihs/sr/statusreport/article/45/5/2, retrieved December 5, 2014.

International Standards Organization (1987). Acoustics—Audible Emergency Signal (ISO Standard 8201), Geneva, Switzerland: International Standards Organization.

Jamson, H., Hibberd D.L., and Merat, N. (2013). The Design of a Haptic Gas Pedal Feedback to Support Eco-Driving., Proceedings of the Seventh International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design, Bolton Landing, NY, 264-270.

Jann, B. (2002). Driver Aggression as a Function of Status Concurrence: An Analysis of Horn-Honking Responses (research report), Bern, Switzerland: University of Bern, Institute of Sociology.

Jeong, H. and Green, P. (2012). Forward Collision Warning Modality and Content: A Summary of Human Factors Experiments (technical report 2012-35), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Jeong, H. and Green, P. (2013). SAE and ISO Standards for Warnings and Other Driver Interface Elements: A Summary (technical report UMTRI-2013-16), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Kiefer, R. J., Cassar, M. T., Flannagan, C. A., LeBlanc, D. J., Palmer, M. D., Deering, R. K., and Shulman, M. A. (2003). Forward Collision Warning Requirements Project: Refining the CAMP Crash Alert Timing Approach by Examining" Last-Second" Braking and Lane Change Maneuvers Under Various Kinematic Conditions (technical report DOTHS-809 574), Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Kiefer, R. J., and Hankey, J. M. (2008). Lane Change Behavior with a Side Blind Zone Alert System, Accident Analysis & Prevention, 40(2), 683-690.

Kidd, D. G., Hagoski, B. K., Tucker, T. G., & Chiang, D. P. (2014). The Effectiveness of a Rearview Camera and Parking Sensor System Alone and Combined for Preventing a Collision With an Unexpected Stationary or Moving Object,~~.~~ Human Factors, online only.

Kiefer, R. J., LeBlanc, D. J., and Flannagan, C. A. (2005). Developing an Inverse Time-to-Collision Crash Alert Timing Approach Based on Drivers' Last-second Braking and Steering Judgments~~.~~, Accident Analysis & Prevention, 37(2), 295-303.

Kim, R., Rauschenberger, R., Heckman, G., Young, D., and Lange, R. (2012). Efficacy and Usage Patterns for Three Types of Rearview Camera Displays during Backing Up (SAE paper 2012-01-0287), Warrendale, PA: Society of Automotive Engineers.

Kochhar, D. S., Talamonti, W. J., and Tijerina, L. (2012). Driver Response to Unexpected Automatic Braking/haptic Warning while Backing, Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Santa Monica, CA: Human Factors and Ergonomics Society, 2211-2215.

Kochhar, D., Talamonti, W., and Tijerina, L., (2013). Considerations in HMI Design of a Reverse Braking Assist (RBA) System (SAE paper 2013-01-0720), Warrendale, PA: Society of Automotive Engineers.

Koustanaï, A., Cavallo, V., Delhomme, P., and Mas, A. (2012). Simulator Training With a Forward Collision Warning System: Effects on Driver-system Interactions and Driver Trust, Human Factors, 54(5), 709-721.

Kozak, K., Pohl, J., Birk, W., Greenberg, J., Artz, B., Blommer, M., Cathey, L., and Curry, R. (2006). Evaluation of Lane Departure Warnings for Drowsy Drivers, Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2400-2404.

Latin, H. (1993). Good Warnings, Bad Products, and Cognitive Limitations, UCLA Law Review, 41, 1193-1295.

Laughery, K. R., Wogalter, M. S., and Young, S. L. (Eds.). (1994). Human Factors Perspectives on Warnings: Selections from Human Factors and Ergonomics Society

Annual Meetings, 1980-1993, Santa Monica, CA: Human Factors and Ergonomics Society.

Laughery, K. R. (2006). Safety Communications: Warnings, Applied Ergonomics, 37(4), 467-478.

LeBlanc, D., Sayer, J., Winkler, C., Ervin, R., Bogard, S., Devonshire, J, Mefford, M., Hagan, M., Bareket, Z., Goodsell, R., and Gordon, T. (2006). Road Departure Crash Warning System Field Operational Test: Methodology and Results. Volume 1: technical report (technical report UMTRI-2006-9-1), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Lee, S.E., Knipling, R.R., DeHart, M.C., Perez, M.A., Holbrook, G.T., Brown, S.B., Stone, S.R., and Olsen, R.L. (2004). Vehicle-Based Countermeasures For Signal And Stop Sign Violations: Task 1. Intersection Control Violation Crash Analyses, Task 2. Top-Level System And Human Factors Requirements (technical report DOT HS 809716), Washington, D.C.: U.S. Department of Transportation.

Lee, J. D., McGehee, D. V., Brown, T. L., and Reyes, M. L. (2002). Collision Warning Timing, Driver Distraction, and Driver Response to Imminent Rear-end Collisions in a High-fidelity Driving Simulator, Human Factors, 44(2), 314-334.

Lee, S.E., Olsen, E.C.B., and Wierwille, W.W. (2004). A Comprehensive Examination of Naturalistic Lane-Changes (technical report DOT HS 809 702), Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration. 6-11, 43-44, 175-177.

Lehto, M. R., & Miller, J. M. (1986). Warnings, Ann Arbor, MI: Fuller Technical Publications.

Lerner, N. D. (1996). Preliminary Human Factors Guidelines for Crash Avoidance Warning Devices (technical report DOT HS 808 342), Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Lerner, N. D., Harpster, J. L., Huey, R. W., & Steinberg, G. V. (1997). Driver Backing-Behavior Research: Implications for Backup Warning Devices, Transportation Research Record # 1573(1), 23-29.

Lerner, N., Jenness, J., Robinson, E., Brown, T., Baldwin, C., Llaneras, R. (2011). Crash Warning Interface Metrics: Final Report (technical report DOT HS 811 470a), Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Lerner, N., Robinson, E., Singer, J., Jenness, J., Huey, R., Baldwin, C., and Fitch, G. (2014). Human Factors for Connected Vehicles: Effective Warning Interface Research

Findings. (technical report. DOT HS 812 068), Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Lin, B.T.W. and Green, P. (2013). Measurements of Driver-Assistance Warning-Signal Characteristics in 2013 Cars (technical report UMTRI 2013-03), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Massie, D. L., Campbell, K. L., and Blower, D. F. (1993). Development of a Collision Typology for Evaluation of Collision Avoidance Strategies, Accident Analysis & Prevention, 25(3), 241-257.

Miller, J. M., Lehto, M. R., and Frantz, J. P. (1990). Instructions & Warnings: The Annotated Bibliography, Ann Arbor, MI: Fuller Technical Publications.

Miller, J. M., & Lehto, M. R. (2001). Warnings and Safety Instructions: Annotated and Indexed, Ann Arbor, MI: Fuller Technical Publications.

Muhrer E., Reinprecht K. and Vollrath M. (2012). Driving With a Partially Autonomous Forward Collision Warning: How Do Drivers React?, Human Factors, 54(5), 700-708.

Muttart, J. W., Hurwitz, D. S., Pradhan, A., Fisher, D. L., and Knodler Jr, M. A. (2011). Developing an Adaptive Warning System for Backing Crashes in Different Types of Backing Scenarios, Journal of Transportation Safety & Security, *3*(1), 38-58.

Najm, W. G., Smith, J. D., & Yanagisawa, M. (2007). Pre-Crash Scenario Typology for Crash Avoidance Research (technical report DOT HS 810 767), Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Nakaoka, M., Raksincharoensak, P., and Nagai, M. (2008, October). Study on Forward Collision Warning System Adapted to Driver Characteristics and Road Environment., International Conference on Control, Automation and Systems, 2008. ICCAS 2008, 2890-2895, IEEE.

National Fire Protection Association (2013). NFPA 72 - National Fire Alarm and Signaling Code Handbook, Quincy MA: National Fire Protection Association.

Neale, V.L., Perez, M.A., Lee, S.E., and Doerzaph, Z.R. (2007). Investigation of Driver-Infrastructure and Driver-Vehicle Interfaces for an Intersection Violation Warning System, Journal of Intelligent Transportation Systems, 11(3), 133-142.

Nober, E.H., Peirce, H., Well, A., Johnson, C.C., and Clifton, C. (1980). Waking Effectiveness of Household Smoke and Fire Detection Device (technical report NBS-GCR-80-284), Washington, D.C.: U.S. Department of Commerce, National Bureau of Standards.

Olsen, E.C.B. (2004). Lane Change Warning Design Guidelines, Proceedings of the

Human Factors and Ergonomics Society 48th Annual Meeting, 2237-2241.

Park H. and Kim K. (2014). AR-Based Vehicular Safety Information System for Forward Collision Warning, Shumaker, R. and Lackey, S. (eds.), Virtual, Augmented and Mixed Reality, Applications of Virtual and Augmented Reality, Springer International Publishing, 435–442.

Peters, G. A., and Peters, B. J. (1999). Warnings, Instructions, and Technical Communications, Tucson, AZ: Lawyers and Judges Publishing Company.

Pierowicz, J., Jocoy, E., Lloyd, M., Bittner, A., and Pirson, B. (2000). Intersection Collision Avoidance Using ITS Countermeasures, Task 9 Final Report, Performance Guidelines (technical report DOT HS 809 171), Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Sayer, J. R., Bogard, S. E.,Buonarosa, M. L., LeBlanc, D.J., Funkhouser, D.S., Bao, S., Blankespoor, A.D., and Winkler, C.B. (2011). Integrated Vehicle-Based Safety Systems, Light-Vehicle Field Operational Test Key Findings Report (technical report DOT HS 811 416), Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Schwartz, G. T. (1990). Myth of the Ford Pinto Case, Rutgers Law Review, 43, 1013-1068.

Shrank, W., Avorn, J., Rolon, C., and Shekelle, P. (2007). Effect of Content and Format of Prescription Drug Labels on Readability, Understanding, and Medication Use: A Systematic Review, Annals of Pharmacotherapy, 41(5), 783-801.

Smith, G.A. Splaingard, M., Hayes, J.R., and Xiang, H., (2006). Comparison of a Personalized Parent Voice Smoke Alarm With a Conventional Residential Tone Smoke Alarm for Awakening Children, Pediatrics, 118(4), 1623-1632.

Smith, M. and Zhang, H. (2004). Safety Vehicles Using Adaptive Interface Technology (Task 9): A Literature Review of Safety Warning Countermeasures (technical report), Kokomo, IN: Delphi Electronics.

Society of Automotive Engineers, (2007). Vehicular Traffic Sound Signaling Devices (Horns), (SAE Standard J377: 2007), Warrendale, PA: Society of Automotive Engineers,

Suzuki, K., and Jansson, H. (2003). An Analysis of Driver's Steering Behavior During Auditory or Haptic Warnings for the Designing of Lane Departure Warning System, JSAE Review, 24(1), 65-70.

Tebeaux, E. (2010). Safety Warnings in Tractor Operation Manuals, 1920-1980: Manuals and Warnings Don't Always Work--, Journal of Technical Writing and Communication, 40(1), 3-28.

Tijerina, L, Johnson, S., Parmer, E., Pham, H.A., Winterbottom, M.D. and Barickman, F.S. (2000). Preliminary Studies in Haptic Displays for Rear-end Collision Avoidance System and Adaptive Cruise Control System Applications (technical report DOT HS 809 151), Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Turner, C.W., Layton, J.F., and Simons, L. S. (1975). Naturalistic Studies of Aggressive Behavior: Aggressive Stimuli, Victim Visibility, and Horn Honking, Journal of Personality and Social Psychology, 31(6), 1098-1107.

U.S. Department of Transportation (2008). National Motor Vehicle Crash Causation Survey (technical report DOT HS 811 059), Washington, D.C.: U. S. Department of Transportation, National Highway Traffic Safety Administration.

U.S. Department of Transportation (2013). Traffic Safety Facts 2012 (technical report DOT HS 812 032), Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

U.S. Department of Transportation, (2014, April 7). Federal Motor Vehicle Safety Standards; Rear Visibility; Final Rule (49 CFR Part 571), Docket No. NHTSA-2010-0162, Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Varhelyi, A. and Makinen, T. (2001). The Effects of In-Car Speed Limiters: Field Studies, Transportation Research Part C, 9, 191-211.

Varhelyi, A. Hjalmdahl, M., Hyden, C., and Draskoczy, M. (2004). Effects of an Active Accelerator Pedal on Driver Behaviour and Traffic Safety after Long-Term Use in Urban Areas, Accident Analysis and Prevention, 36, 729-737.

Visvikis C., Smith T.L., Pitcher M., and Smith R. (2008). Study On Lane Departure Warning and Lane Change Assistant Systems (technical report PPR 374 project report 27-30), Crowthorne, UK: Transport Research Laboratory, 32-37, 39-40.

Wogalter, M. S. (2006). Handbook of Warnings, Mahwah, N.J.: Lawrence Erlbaum Associates.

Wogalter, M. S., Conzola, V. C., and Smith-Jackson, T. L. (2002). Research-Based Guidelines for Warning Design and Evaluation, Applied Ergonomics, 33(3), 219-230.

Wogalter, M. S., DeJoy, D., and Laughery, K. R. (Eds.). (2005). Warnings and Risk Communication, Boca Raton, FL: CRC Press.

Wogalter, M. S., Laughery, K. R., and Mayhorn, C. B. (2012). Warnings and Hazard Communications in Salvendy, G. (ed.), Handbook of Human Factors and Ergonomics, (4th ed.), 868-894.

Wolf, M. S., Davis, T. C., Shrank, W., Rapp, D. N., Bass, P. F., Connor, U. M., and Parker, R. M. (2007). To Err is Human: Patient Misinterpretations of Prescription Drug Label Instructions, Patient Education and Counseling, 67(3), 293-300.

Ursic, M. (1985). Product Safety Warnings: A Legal Review, Journal of Public Policy and Marketing, 80-90.