

Seniors face serious driving safety and mobility issues.



Keeping Older Adults Driving Safely: A Research Synthesis of Advanced In-Vehicle Technologies

A LongROAD Study

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Title

Keeping Older Adults Driving Safely: A Research Synthesis of Advanced In-Vehicle Technologies. (December 2015)

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About the Sponsor

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About LongROAD

Safe mobility is essential to healthy aging. Recognizing that lifestyle changes, along with innovative technologies and medical advancements, will have a significant impact on the driving experiences of the baby boomer generation, the AAA Foundation for Traffic Safety has launched a multi-year research program to more fully understand the driving patterns and trends of older drivers in the United States. This multi-year prospective cohort study is being conducted at 5 sites throughout the country, with 3,000 participants, tracking 5+ years of driving behaviors and medical conditions. The multidisciplinary team assembled to investigate this issue is led by experienced researchers from Columbia University, University of Michigan Transportation Research Institute and the Urban Institute.

The LongROAD (Longitudinal Research on Aging Drivers) Study is designed to generate the largest and most comprehensive data base about senior drivers in existence and will support in-depth studies of senior driving and mobility to better understand risks and develop effective countermeasures. Specific emphasis is being placed on issues related to medications, medical conditions, driving patterns, driving exposure, self-regulation, automotive technologies, and crash risk, along with mobility options for older Americans who no longer drive.

Abstract

Background

Advanced in-vehicle technologies have been proposed as a potential way to keep older adults driving for as long as they can safely do so, by taking into account the common declines in functional abilities experienced by older adults.

Objectives

The purpose of this report was to synthesize the knowledge about older drivers and advanced in-vehicle technologies, focusing on three areas: use (how older drivers use these technologies), perception (what they think about the technologies), and outcomes (the safety and/or comfort benefits of the technologies).

Methods

Sixteen technologies were selected for review and grouped into three categories: crash avoidance systems (lane departure warning, curve speed warning, forward collision warning, blind spot warning, parking assistance, intersection assistance, merging assistance); in-vehicle information systems (navigation assistance, congestion warning, intelligent speed adaptation); and other systems (adaptive cruise control, automatic crash notification, night vision enhancement, adaptive headlight, voice activated control, drowsiness/fatigue warning). A comprehensive and systematic search was conducted for each technology to collect related publications. 298 articles were included into the final review.

Results

Research findings for each of the 16 technologies were synthesized in relation to how older adults use and think about the technologies as well as potential benefits. These results are presented separately for each technology. The paper also addresses training, education, and research needs.

Conclusions

Can advanced in-vehicle technologies help extend the period over which an older adult can drive safely? This report answers this question with an optimistic "yes." Some of technologies reviewed in this report have been shown to help older drivers avoid crashes, improve the ease and comfort of driving, and travel to places and at times that they might normally avoid. Other technologies show promise for providing benefits to older drivers and the development of these technologies continues.

Introduction

For decades demographers have predicted the aging of the United States (US) population and the effects that this demographic shift will have on society. Indeed, with the first Baby Boomers reaching the age of 70 in 2016, this so-called "aging tsunami" (Seville, 2014) has arrived and will continue for several decades. The world's population is also aging. According to the report "Global Health and Aging" (National Institute on Aging, NIA, 2011), the world's population is older now than at any other time in history. By 2016, the global number of older adults (aged 65 and older) will be greater than the number of children age 5 and under, with projections showing that the number of older adults will increase from 524 million in 2010 to 1.5 billion in 2050 (NIA, 2011).

Aging and Driving

As the global population continues to grow older, the personal automobile will increasingly be the preferred mode of personal mobility (Eby & Molnar, 2014). The reasons for this trend are numerous. First, in the US and in many other countries, the coming cohort of older adults tend to link driving a personal automobile with continued independence and a high quality-of-life (Molnar & Eby, 2009). Second, studies on older adults have found that an association between driving cessation and declines in well-being and many other important health measures (Chihuri et al., 2015; Edwards et al., 2009; Marottoli et al., 1997; Ragland, Satariano, & MacLeod, 2005; Windsor et al., 2007). Third, in nearly all countries, the licensure rate for older adults is increasing and will likely continue to increase (Sivak & Schoettle, 2011). Fourth, in addition to the increasing number of licensed older adults, this age group is expected to drive more than previous cohorts (Buehler & Nobis, 2010; Santos, McGuckin, Nakamoto, Gray, & Liss, 2011). Finally, non-driving community mobility options are lacking or insufficient in many locations (McGuckin & Srinivasan, 2003), particularly in rural areas where a higher concentration of older adults are located (Kostyniuk et al., 2012). Thus, for most older adults the automobile is the only viable option for personal mobility whether they are a driver or a passenger.

Crashes

The debate continues about whether older drivers are at a greater risk of a crash when compared to drivers age 25-64 years (see e.g., Alvarez & Fierro, 2008; Eby, Molnar, & Kartje, 2009; Hakamies-Blomqvist, Raitanen, & O'Neill, 2002; Insurance Institute for Highway Safety, IIHS, 2014; Langford, Methorst, & Hakamies-Blomqvist, 2006; Staplin, Gish, & Joyce, 2008). There is, however, general agreement that older adults are at higher risk for fatal crashes. Figure 1 shows the fatal crash rate per 100 million miles traveled by age group in the US in 2008 (IIHS, 2013). Fatal crash rates declined up to about age 30 and then sharply increased after age 69.

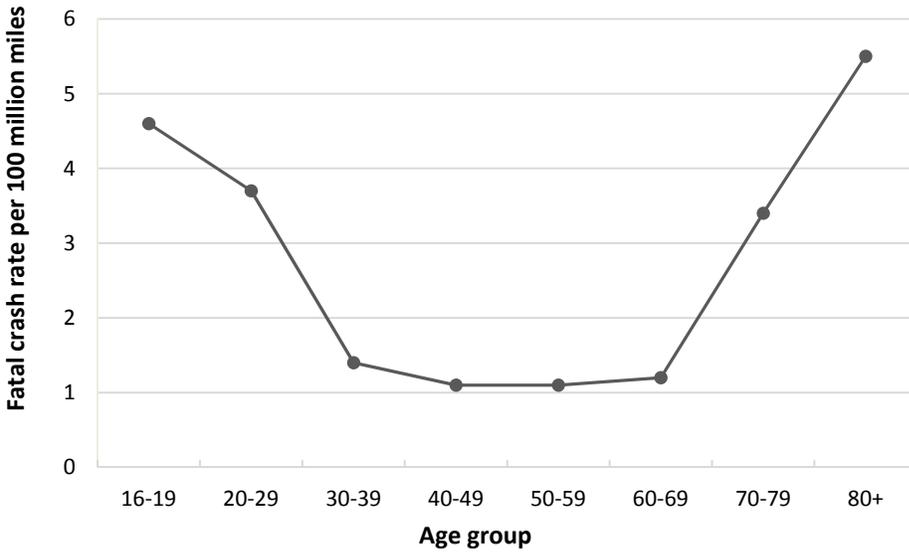


Figure 1: Passenger Vehicle Fatal Crash Rates per 100 Million Miles Driven by Driver Age Group for the US in 2008. Data are from IIHS (2013).

Several studies have documented that older adults are involved in different types of crashes than younger drivers, in particular intersection crashes (see e.g., Abdel-Aty & Radwan, 2000; Clark, Forsyth, & Wright, 1999; Cooper, 1990; Hakamies-Bloomqvist, 2004; Langford & Koppel, 2006; Larsen & Kines, 2002; Oxley, Fildes, Corben, & Langford, 2006; Staplin, Lococo, McKnight, McKnight, & Odenheimer, 1998). Figure 2 shows fatal crash data from the US in 2013 by intersection versus non-intersection crashes for single and multiple vehicles by age group (IIHS, 2013). The graph shows that the percentage of all fatal crashes involving multiple vehicles at intersections increases consistently after age 30 with a steep increase after age 79, while no increase was found for single-vehicle intersection crashes across the lifespan. Considering non-intersection crashes (dashed lines), there was a consistent reduction in the percentage of fatal non-intersection single vehicle crashes with age and a steep decrease in the percentage on non-intersection multiple vehicle crashes after age 79. Thus, these data support the notion that intersections with traffic pose a significant safety risk for older drivers.

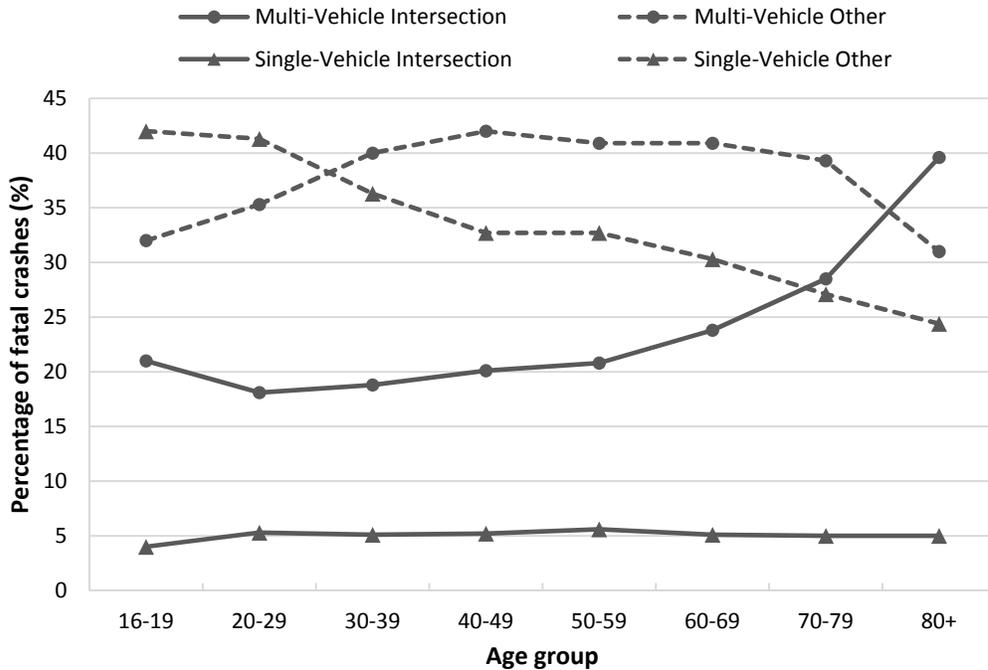


Figure 2: Percentage of Fatal Crashes by Age Group and Crash Type in 2013. Data are from IIHS (2013).

Aging, Health, and Driving Abilities

Driving is a complex task that involves three broadly categorized functional abilities: psychomotor, visual, and cognitive. As stated by several researchers in the field of aging and driving, age per se is not necessarily associated with driving problems; rather, as people age they may experience declines in these driving abilities as a result of age-related medical conditions and the medications used to treat these conditions (see e.g., Dickerson et al., 2007). While a detailed review of health and driving abilities is out of the scope of this paper, a short review of these findings is useful. Detailed summaries of the aging, health, and driving literature can be found in several documents (Charlton et al., 2004; Dobbs, 2005; Eby et al., 1998; Eby, Molnar, & Kartje, 2009; Janke, 1994).

Psychomotor Abilities

Psychomotor functioning refers to a person's ability to move and orient parts of his or her body (Kelso, 1982). While there is great individual variability, studies show that in general older adults have slower simple and choice reaction times (e.g., Marottoli & Drickamer, 1993); decreased flexibility (Malfetti, 1985; McPherson, Michael, Ostrow, & Shafron, 1988); decreased coordination (Anshel, 1978; Marshall, Elias, & Wright, 1985); and a significant reduction in strength and muscle mass (e.g., Petrofsky & Lind, 1975; Shepard, 1998). Collectively, these declines can result in older drivers having difficulties getting into and out of vehicles; using cargo areas; engaging in certain operational behaviors, such as turning the head to check blind spots; and traveling for long periods of time (Janke, 1994; Malfetti, 1985; Marottoli et al., 1998; Shaw, Polgar, Vrkljan, & Jacobson, 2010; Sivak et al., 1995; Staplin et al., 1999).

Visual Abilities

In terms of driving, perceptual abilities mainly refer to vision in that safe driving is largely dependent upon visual information. Declines in visual abilities are common in older adulthood due mainly to the higher likelihood of diseases of the visual system (Anstey, Wood, Lord, & Walker, 2005; Attebo, Mitchell, & Smith, 1996). Again, while there is large individual variability, a number of visual abilities tend to get worse with age. These include: declines in static and dynamic visual acuity (Burg, 1966; Heron & Chown, 1967; Long & Crambert, 1989; Owsley & Sloane, 1990); decreased sensitivity to light (Birren & Shock, 1950; McFarland, Domey, Warren, & Ward, 1960); increased glare recovery durations (Wolf, 1960); decreased contrast sensitivity (Owsley, Sekuler, & Siemsen, 1983; Schieber, Kline, Kline, & Fozard, 1992); shrinking of the so-called useful field of view (Ball, Beard, Roenker, Miller, & Griggs, 1988; Scialfa, Kline, & Lyman, 1987; Sekuler & Ball, 1986); reduced sensitivity to visual motion (Ball & Sekuler, 1986; Schieber, Hiris, White, Williams, & Brannan, 1990); and possibly less veridical depth perception (Bell, Wolf, & Bernholz, 1972; Hofstetter & Bertsch, 1976; Jani, 1966). Because of the importance of vision for driving, declining visual abilities can make it difficult for older adults to drive at night, read traffic signs and lane markings, judge gaps in traffic while merging, change lanes, and make turns at intersections.

Cognitive Abilities

Cognitive or thinking abilities are clearly critical for safe driving, as these are the abilities that allow a driver to understand driving situations and make appropriate and timely operational, strategic, tactical, and life goal decisions about driving (Eby, Molnar, & Kartje, 2009; Michon, 1985). As with other abilities, cognitive abilities vary greatly among older adults, but several cognitive abilities tend to show declines with aging. These include: divided attention and selective attention (Ponds, Brouwer, & van Wolffelaar, 1988; Salthouse, Mitchell, Skovronek, & Babcock, 1989); processing speed (French, West, Elander, & Wilding, 1993; West, Crook, & Barron, 1992); spatial cognition (Salthouse, 1987); memory (e.g., Eby et al., 2012); and executive function (see e.g., Anstey et al., 2005; Daigneault, Joly, & Frigon, 2002; Mayr, Spieler, & Kliegl, 2001; Zelazo, Craik, & Booth, 2004). Cognitive declines can make driving unsafe in a myriad of driving situations including: driving in heavy traffic; negotiating intersections; driving under heavy workloads; driving in unfamiliar areas; and making appropriate decisions on how to self-regulate driving (i.e., modify one's driving by driving less or avoiding situations in response to declining abilities).

Fragility/Frailty

Another set of general health factors associated with driving and thought to be important contributors to the increase risk of fatal crashes in older adulthood are fragility and frailty (Langford & Koppel, 2006; Organization for Economic Co-operation and Development, OECD, 2001; Koppel, Bohensky, Langford, & Taranto, 2011). In reference to traffic safety, a person who is more fragile will sustain a greater level of injury for a given crash force (Kent, 2010; Kent, Trowbridge, Lopez-Valdes, Ordoyo, & Segui-Gomez, 2009). Frailty can be thought of as the ability to recover from the injury (see e.g., Fillit & Butler, 2009; Heppenstall, Wilkinson, Hanger, & Keeling, 2009; Szanton, Seplaki, Thorpe, Allen, & Fried, 2010; Yunkyung, Gruenewald, Seeman, & Sarkisian, 2010).

Can in-Vehicle Technology Help Extend Safe Driving?

In an effort to keep people driving for as long as they can safely do so, several researchers have recently proposed that vehicle designs and advanced in-vehicle technologies could be optimized to take into account the common declines in functional abilities experienced by older adults (see e.g., Band & Perel, 2007; Eby & Molnar, 2014; Marshall, Chrysler, & Smith, 2014; Meyer, 2009; Paris et al., 2014). Such optimization and advanced technologies should make driving easier, safer, and more enjoyable for older adults.

The focus of this literature synthesis is advanced vehicle technologies and older drivers. Two lists of technologies believed to be particularly relevant for older driver safety have been published recently. The first was published as a newspaper article and lists the following seven in-vehicle technologies to help older adults compensate for declining abilities (Mulholland, 2009): heads-up displays; pre-crash warning systems; pedestrian detection; lane departure warning; adaptive headlights and night vision; blind spot detection; and intelligent parking assist. The second list was developed by the Hartford Insurance Company and the MIT AgeLab through a nationwide survey of drivers age 50 and older and the opinions of seven experts on aging and driving (The Hartford, 2012). They concluded that the following in-vehicle technologies could provide the greatest benefit to older drivers: smart headlights; emergency response systems; reverse monitoring systems; blind spot warning systems; lane departure warning; electronic vehicle stability control; assistive parking systems; voice activated systems; crash mitigation systems; and drowsy driver alerts. In a project sponsored by the AAAFTS (Mehler et al., 2014b), the overall safety benefits of advanced technologies for all drivers, including older drivers, was assessed and the following 7 technologies were judged to have at least some benefit: electronic stability control; backup cameras; adaptive headlights; lane departure warning; adaptive cruise control; forward collision warning; forward collision mitigations

The purpose of this report was to synthesize the knowledge about older drivers and advanced in-vehicle technologies from a variety of sources, such as the ones mentioned previously. Specifically, this synthesis focuses on information about how older drivers use these technologies, what they think about the technologies, and the safety and/or comfort benefits of the technologies. This synthesis is limited to manufacturer-installed advanced technologies. As such, nomadic devices (e.g., cellular phone applications) and aftermarket technologies are excluded. Also excluded is electronic stability control (ESC) technology for the following reasons: the safety benefits of ESC are well established (see e.g., Chouinard & Lécuyer, 2011; Dang, 2007; Ferguson, 2007; Sivinski, 2011), the technology does not require interaction with the driver and the presence of ESC has been required on all light vehicles in the US since 2012 (National Highway Traffic Safety Administration, NHTSA, 2015). Vehicle design issues and advanced crashworthiness technologies (such as inflatable seatbelts) are also not covered, as these topics have been reviewed recently elsewhere (see e.g., Eby & Molnar, 2014). Finally, the review excludes autonomous vehicle (also called “driverless car” and “self-driving car”) technologies, as these are still under development and not available from a vehicle manufacturer.

This report builds on previous research conducted by the authors (Eby & Molnar, 2014). In this previous work, we explored vehicle design issues, six advanced in-vehicle technologies, crashworthiness issues, and the potential challenges to marketing a vehicle design for older

drivers. The present report updates and greatly expands upon the in-vehicle advanced technology discussed in the previous report as well as discussing many other technologies and issues not addressed in that report.

Methods

The search for literature on advanced in-vehicle technologies and older drivers entailed a number of steps. First, we developed a list of the new advanced in-vehicle technologies that might benefit older drivers based on previous research (Eby & Molnar, 2014; Eby, Molnar, & Kartje, 2009; Mulholland, 2009; The Hartford, 2012; Mehler et al., 2014b) and the expertise of the research team. Based on this, 16 technologies were selected and grouped into three categories as shown in Table 1.

Table 1: Categorization of advanced vehicle technologies and records of literature search

Category	Advanced In-Vehicle Technology	Number of articles identified	Number of articles reviewed
Crash avoidance systems	Lane departure warning/mitigation (LDW)	821	29
	Curve speed warning (CSW)	144	4
	Forward collision warning/mitigation (FCW)	134	29
	Blind spot warning (BSW)	274	22
	Parking assistance (PA)	140	25
	Intersection assistance (IA)	52	21
	Merging assistance (MA)	84	6
In-vehicle information systems	Navigation assistance (NA)	139	27
	Congestion warning (CW)	65	8
	Intelligent speed adaptation (ISA)	316	31
Other systems	Adaptive cruise control (ACC)	153	38
	Automatic crash notification (ACN)	173	12
	Night vision enhancement (NVE)	78	13
	Adaptive headlight (AH)	250	23
	Voice activated control (VAC)	173	18
	Drowsiness/fatigue warning (DW)	461	29
Total		3,457	335

Publications on each of these technologies were searched comprehensively in SCOPUS, TRID, and DEEPBLUE (a digital repository of University of Michigan reports). From these databases, we gathered relevant journal articles, conference papers, technical reports, and books with the restriction that they be published in English. To aid in finding articles related to these technologies and older drivers, search terms were developed for three parameters: the various names for each technology; terms used to describe the older adult population (e.g., older, elderly, aged, aging, senior, and mature); and terms that restricted results to the driving domain (e.g., driving, driver, vehicle, and automobile). For some technologies for which there was little literature, we did not restrict our search to only older adults. In addition, the search was not restricted by year, but most studies found in the review were published in the 1990s onward. Manual searches of the reference lists of

selected key articles were also conducted to collect additional relevant articles. As shown in Table 1, the initial search yielded more than 3,400 articles.

Articles produced from this search were then reviewed for appropriateness. To be included for further review, the study had to meet several criteria: 1) be related to how older drivers use, think about, or are affected by the specific in-vehicle technologies; 2) focus on the safety and mobility benefits of these technologies, rather than the environment, congestion, or other benefits; and 3) either address older drivers specifically or include older drivers as part of the larger population being addressed. Due to a general lack of studies utilizing an older driver group, this criterion was relaxed for some technologies for which associated studies included more than just young drivers. This review process yielded a total 335 articles. The number of articles per technology is shown in Table 1. Because 37 articles addressed more than one technology, the actual number of unique articles was 298.

In reviewing the 298 articles, we were interested in discerning: 1) how older drivers use these technologies (e.g., frequency of use, misuse or abuse, behavioral adaptation, prevalence, use barriers); 2) how they think about the technologies (e.g., acceptance, trust, satisfaction, general opinions); and 3) how the technology influences behaviors or safety outcomes (e.g., behavioral changes, crash reduction, workload, situation awareness, distraction). The articles represented a wide range of research methods including questionnaires, focus groups, structured interviews, crash record analysis, naturalistic driving, and simulated driving. Relevant articles for each technology were reviewed and the knowledge was synthesized by the authors.

Results

The results are presented by the three categories of advanced in-vehicle technologies outlined earlier: crash avoidance systems; in-vehicle information systems; and other systems. It is important to note that this categorization is somewhat artificial and that some of the technologies fit into more than category. For example, parking assistance technologies span the range of assistance from simply providing a rear-view camera to automatically parallel parking a vehicle. Technologies in the first group would be categorized as in-vehicle information systems while technologies in the latter group would be categorized as crash avoidance systems given that they can help prevent a crash. In these cases we simply chose a category for the technology and synthesized all of the information for that technology in one place.

Crash Avoidance Systems

One particularly promising category of technologies involves systems that directly target the prevention of crashes. These systems, collectively called crash avoidance systems, use on-vehicle radars, cameras, other sensors, and computer intelligence to determine the situations that could lead to a crash. When a potentially hazardous situation arises, the system either provides a warning to the driver that an action may be required, or takes over temporary control of an operational aspect of the vehicle (such as braking) and engages that system without driver input to avoid a crash. This section reviews the following technologies: lane departure warning systems; curve speed warning systems; forward collision warning systems; blind spot warning; parking assistance systems; intersection assistance systems; and merging assistance systems.

Lane Departure Warning/Mitigation

A number of technologies have been developed in recent years that are designed to keep a driver from inadvertently driving outside of a travel lane, thereby assisting the driver in proper lane keeping behavior and ultimately preventing run-off-the-road crashes. Lane departure warning/mitigation (LDW) systems (also called Lane Keeping Assistance and Lateral Drift Warning Systems) utilize video camera and image analysis software to determine the location of lane markings relative to the vehicle (LeBlanc et al., 2006). When the vehicle drifts too close to the markings without a turn-signal activated, the driver is given some form of an alert that is most often directionally-linked such that a drift to the left is accompanied by a visual (e.g., flashing icon), auditory (e.g., beep), or haptic (e.g., slight steering wheel force in the direction away from the drift) warning on the driver's left side. In some cases, the system can also take partial control of the vehicle to help maintain proper lane position. For example, some commercially-available systems, in addition to the warning, can also apply slight brake pressure to the wheel opposite the lane departure to help move the vehicle back into the center of the lane (Braitman, McCartt, Zuby, & Singer, 2010).

A number of studies have estimated the safety benefits of LDW systems under the scenario that the light-vehicle fleet in the US was equipped with the systems and all drivers used them. Under a variety of assumptions, the safety benefits of LDWs have been estimated across the entire US population of drivers as leading to an overall reduction in all crashes of

about 3 percent, all lane-departure-related crashes of about 30 percent, lane-departure crashes with serious injury of about 25 percent, and lane-departure fatal crashes of about 10-20 percent (Blower, 2014; Jermakian, 2011; Kusano & Gabler, 2014; Kusano, Gorman, Sherony, & Gabler, 2014). Studies looking specifically at the estimated crash reduction benefits among the older population have not been published.

Little research has addressed older drivers' use of LDW systems. A number of studies that utilized simulators have investigated the effectiveness of various types of alerts to help drivers respond appropriately to the warning (Cummings, Kilhore, Wang, Tijerina, & Kochhar, 2007; Deroo, Hoc, & Mars, 2012; Edwards, Morris, & Manser, 2013; Kozak, et al., 2006; Navarro, Mars, & Hoc, 2007; Suzuki & Jansson, 2003). None of these studies focused specifically on older adults. Collectively, the results showed that haptic warnings (particularly small pulses to the steering wheel in the direction of the center of the travel lane) accompanied by an auditory warning, resulted in the fastest and most accurate driver response. Warnings that were directionally-linked were more effective than those that were not. These results would likely hold for older adults, but this should be confirmed in further research.

Studies making use of instrumented vehicles on actual roadways also shed light on the safety benefits of LDW systems. One such study in Germany investigated the lane keeping performance among 30 drivers (some as old as 65 years) who were asked to dial a phone while driving a vehicle equipped with a LDW system (Blaschke, Breyer, Färber, Freyer, & Limbacher, 2009). The study found significantly better lane keeping while dialing the phone when the LDW system was providing alerts (steering wheel vibration in this case). Departures from the travel lane were found only in the conditions where the LDW was turned off. The LDW system was also judged to be helpful by the participants. No analyses by age were presented.

In an investigation of 78 people (26 of which were aged 60-70) in Michigan using a LDW system in over 83,000 miles of driving, LeBlanc et al. (2006) found that the system induced drivers to stay closer to the center of the lane, use their turn signals more often when changing lanes, and reduced the frequency of lane excursions. When compared to younger age groups, the older group in the study judged the LDW system to be more useful.

The assessment of LDW systems among older drivers has been mixed in other global studies that have utilized focus group and interview techniques. A focus group study in Australia (Regan, Mitsopoulos, Haworth, & Young, 2002) found that older drivers (age 65 and older): thought that LDW systems would be useful, especially for long trips; expressed uncertainty about the effectiveness of LDW systems, particularly in various weather and road conditions; were concerned about whether the system could give them a warning that was early enough for them to take a corrective action; and expressed some concern that the system would lead to distraction. A German study that interviewed 32 drivers age 60 to 80 years who owned vehicles equipped with driver assistance systems (not necessarily a LDW system) expressed moderate concerns about the effectiveness and usefulness of LDW systems, but most had little actual experience with these systems (Trübswetter & Bengler, 2013). In a focus group study in Sweden of drivers age 39 to 74 who drove vehicles equipped with some form of advanced driver assistance system, participants indicated that they used their turn signals more often with the LDW system, but expressed concern about the system not working in all driving conditions (Strand, Nilsson, Karlsson, & Nilsson, 2011).

A study in the US interviewed 183 owners of vehicles equipped with LDW systems (Eichelberger & McCartt, 2014). Nearly half of the participants were age 61 and older. This study found that 71 percent of participants wanted an LDW system on their next vehicle and most reported that they drove more safely when using the LDW system. Finally, another US study interviewed 301 drivers of vehicles with LDW warnings only (10 percent were age 61 and older) and 184 drivers of vehicles with LDW that also actively helped to steer the vehicle back to the center of the lane, where 19 percent were age 61 and older (Braitman, McCartt, Zuby, & Singer, 2010). Of those drivers in the LDW-warning-only group: 69 percent reported always used the system; 47 percent reported receiving erroneous warnings, usually in situations where lane markings were poor or covered; 71 percent reported that the system helped them with proper lane keeping; 75 percent said the system made them a safer driver; 54 percent reported using their turn signals more often; 34 percent said the system relieved stress; and 41 percent thought the system was annoying. Of the respondents who had a LDW prevention system (i.e., one that helped to steer back into the lane center) in their vehicle: 15 percent always had the system turned on; 22 percent were unaware that their vehicle had the system; and 22 percent never used the system (note that this system defaulted to off and had to be turned on for each trip). Of those who had used the system: 10 percent reported getting false or unnecessary warnings; 15 percent thought the intervention component of the system was annoying; 68 percent reported drifting less often in their lane; 64 percent reported using their turn signals more often; and 83 percent expressed that they would want the system again.

Curve Speed Warning

A system that is closely related to lane departure warning systems, are curve speed warning (CSW) systems which use global positioning system (GPS) information and digital maps to determine the risk associated with a vehicle approaching a curve at a certain speed and warns that driver if the approach speed is too fast for the curve (University of Michigan Transportation Research Institute, UMTRI, 2015). Only a handful of studies have addressed CSW systems with older adults.

One of these studies compared 24 young drivers (aged 18-25) to 24 older drivers (aged 60 and older) on responses to combinations of three CSW alert types: visual (a flashing numeral that indicated the proper speed); auditory (a voice instructing the driver on the proper speed); and haptic (3-second force on the accelerator pedal against the driver's foot; McElheny, Blanco, & Hankey, 2006). Drivers were tested at night on a closed driving course. Overall, drivers exhibited quicker reaction times and more appropriate speeds at curves when they received a CSW than in a baseline condition with no warning. The older drivers were significantly closer than the young drivers to the appropriate speed in response to the CSW. The older drivers were also significantly more likely to want a CSW system in their vehicle that included a visual-auditory-haptic set of warning types.

Another study tested a CSW system over a 1-month period in which 78 drivers (26 of whom were aged 60 and older) drove a test-vehicle equipped with both a CSW and LDW system in a natural setting (LeBlanc et al., 2006). The CSW system utilized a combination of visual (icon), auditory (message), and haptic (seat vibration) warnings. Overall, the CSW system did not significantly change objective curve-taking behaviors (analyses on this issue by age

group were not presented). Participant ratings of the CSW system were generally positive, with older drivers giving slightly more positive ratings.

A final study investigated an integrated set of crash-avoidance technologies that included a CSW component (Sayer et al., 2010). One-hundred eight volunteers (36 of whom were age 61-69) drove a test vehicle for a 40-day period using it as their personal vehicle. During the final 30 days of the study, the crash avoidance technologies were operational. As with the previous study, there was no significant change in objective curve-taking behaviors either when approaching or when negotiating curves. Of the other components in the system, the CSW component was rated as one of the least useful. No analyses by age were reported for this component of the integrated system.

Forward Collision Warning/Mitigation

Forward collision warning/mitigation (FCW) systems use forward radars and other sensors to determine the changing distances to vehicles and objects in front of the driver's vehicle. When the system determines that the vehicle is in danger of colliding with the forward obstacle, the system will warn the driver using some signal (usually a combination of a light and sound) and, in some systems, take over partial control (e.g., braking) of the vehicle. FCW has great potential for preventing crashes and the associated death and injuries. Nationally, studies estimated that with full-market penetration, FCW systems could prevent up to 20 percent of all crashes (Blower, 2014; Jermakian, 2011; Kusano & Gabler, 2014). This translates into an annual reduction of 1.2 million crashes, 66,000 non-fatal injuries, and 879 fatalities (Jermakian, 2011). Unfortunately, there are no estimates of crash reduction by age of driver.

Several studies have investigated the use, perceptions, and benefits of FCW systems utilizing driving simulators in scenarios that involve high risk for a frontal crash, such as a lead vehicle suddenly braking. These studies have found that: FCW systems reduced crash likelihood; driver acceptance was high when the system did not give too many false alarms (giving alerts when they were not appropriate); older drivers were more forgiving of false alarms when they understood the cause of the false alarm; older drivers reacted just as quickly to collision events as younger drivers, even though the older participants had slower reaction times in a laboratory setting; and older participants drove more slowly than younger drivers and maintained longer headways from the next vehicle when using the system (Cotté, Meyer, & Coughlin, 2001; Kramer et al., 2007; Maltz & Shinar, 2004).

These systems were also tested on roadways (either on closed test-track or on actual roads) with instrumented vehicles in several studies. In a study on a closed test-track with an instrumented vehicle equipped with a FCW system, researchers found that older participants maintained longer headways when compared to young drivers, similar to what was found with the simulator studies. Further, the headways for older participants did not change as false alarms increased, indicating that older drivers were more tolerant of false alarms (Dingus et al., 1997). A study in Italy tested a FCW system in controlled drives in real city traffic utilizing an instrumented vehicle equipped with a FCW system (Adell, Vårhelyi, & Fontana, 2011). This study included 20 drivers, 10 of whom were age 45-69. The study found that drivers reacted more quickly to threats, drove with longer headways, and were better able to detect pedestrians in the roadway while using the system. On the negative side, when using the system drivers had significantly more center lane crossings

and harder braking at traffic lights. No other safety-related driving behaviors were impacted.

Two large-scale field operational tests have evaluated FCW systems with drivers under natural driving conditions (Ervin et al., 2005; LeBlanc, Bao, Sayer, & Bogard, 2013; Sayer et al., 2010). One third of the roughly 100 participants in each study were age 60-70. In both studies, participants drove instrumented vehicles that were equipped with a FCW system (and other crash avoidance systems) for 1 week with the system turned off and then 3 additional weeks with the system operational. Participants were instructed to drive as they normally would. The instrumented vehicles recorded a wide range of measures automatically as participants drove. Collectively, these studies found: when compared to not using the system, the FCW system improved safety for all drivers and did not impact other safety behaviors such as engaging in more frequent secondary tasks while driving; older participants were more likely to view the system favorably, although most judged the system usefulness as neutral; older participants drove with more distance from the lead vehicle than participants in other age groups; many drivers reported receiving alerts that were not necessary; and many drivers thought that the system would improve safety, but generally this perception was directed at other age groups rather than their own.

Several studies have conducted focus groups and interviews with drivers (the percent of participants age 60 and older in each study ranged from 26 percent to 56 percent) who had a FCW system on their personal vehicles (Braitman et al., 2010; Cicchino & McCartt, 2014; Eichelberg & McCartt, 2014a, 2014b; Strand et al., 2011). The results of these subjective studies are fairly consistent and show: a large majority of drivers (84 percent to 97 percent) always kept the system on; 40 to 55 percent of drivers had received alerts from the system and about one-half thought the system helped to prevent a crash; slightly more than one-half of respondents reported that the system never failed to warn them of a crash, but a larger percentage also believed they received false alarms; and participants generally reported that the system made them more aware of following distances and some reported driving with a greater following distance when using the system.

Blind Spot Warning

To safely change lanes, it is important for a driver to ensure that the lane he or she intends to enter is not blocked by another vehicle, bicycle rider, or other obstacle, through a direct visual search of the area surrounding the vehicle and a scan of the mirrors. If the driver does not turn his or her head to check for traffic, there are areas around the vehicle where objects cannot be seen even in side-view mirrors (the blind spot), putting the driver at higher risk of crash. A simulator study comparing blind spot checking among younger (age 21-31) and older (age 65-75) drivers found that the older drivers checked blind spots significantly less frequently (41 percent versus 86 percent) and older drivers turned their heads less far when they did check the blind spot (Lavallière, Laurendeau, Simoneau, & Treasdale, 2011). A study using an instrumented vehicle under actual highway driving conditions found that older drivers were less than half as likely (24 percent versus 53 percent) to check the blind spot during a lane change (Lavallière, Reimer, et al., 2011).

Blind sport warning (BSW) systems use radars or cameras to monitor the location of traffic or obstacles in a vehicle's blind spot zones and provide warnings to the driver about these obstacles during a lane change maneuver (Kessler et al., 2012; Jermakian, 2011). As with

most collision avoidance systems, these warnings can be visual, auditory, or haptic (see e.g., Chun et al., 2013; Guo, Wotring, & Antin, 2010). These systems are also called side-view assist, blind spot monitor, and lane change/merge assist. BSW systems are designed to help prevent lane-change-related crashes. According to one estimate, if all US vehicles were equipped with BSW systems, about 20,000 moderate-to-severe injuries and 393 fatal crashes each year could be prevented (Jermakian, 2011).

A European study that examined safety-related behaviors of middle-age drivers while using a BSW system found that turn-signal use decreased significantly (about 10 percent) when compared to the same drivers not using the system (Kessler et al., 2012). A simulator study also found a decreased use of turn signals among older adults (Guo, Wotring, & Antin, 2010). This result seems counterintuitive, but subjective data from these studies showed that drivers trusted the system to let them know if a vehicle was in the intended lane, so the turn signal did not seem as important. When a BSW system is combined with a LDW system, however, turn signal use has been shown to increase (Sayer et al., 2010). This same study, which included an older adult age group, found that when using the BSW system, participants adjusted their lane position slightly away from vehicles in the blind spot, indicating that the BSW increased driver awareness of adjacent traffic. Test-track results with middle-age participants indicated that a BSW system helped drivers react more quickly to a lateral crash threat and drivers reported that they liked receiving the BSW alerts (Fitch, Bowman, & Llaneras, 2014). A study that utilized test vehicles with a BSW system being driven in actual traffic with drivers age 40-70 found that mirror-checking prior to a lane-change significantly increased (Kiefer & Hankey, 2008).

Several studies have reported subjective impressions of a variety of BSW systems among older drivers. Collectively, these studies have found: there are concerns about the system accuracy and false alarms, particularly in bad weather; mixed results about whether older adults would want the system in a future car; and some older adults reported that the system could be distracting (Cicchino & McCartt, 2014; Braitman, McCartt, Zuby, & Singer, 2010; Strand, Nilsson, Karlsson, & Nilsson, 2011; Trübswetter & Bengler, 2013). Findings from large-scale interview studies of drivers (about 30 percent of whom were age 61 or older) with BSW systems in their personal vehicle indicated that: the system had helped to prevent a lane-change crash; the system was used frequently; high levels of system reliability were reported but also there were frequent reports of false warnings, generally during bad weather; little change in turn signal or mirror use; less frequent turning of the head to check a blind spot in about one-third of participants; and the system made users feel safer and less stressed (Braitman, McCartt, Zuby, & Singer, 2010; Cicchino & McCartt, 2014).

Parking Assistance

An unavoidable component of driving is the need to park. Studies have long shown that many older drivers have difficulty parking and often rate parking, particularly parallel parking, as stressful (Baldock, Mathias, McLean, & Berndt, 2006; Douissebekov et al., 2014; Herriotts, 2005; Lyman, McGwin, & Sims, 2001; Parker, Macdonald, Sutcliffe, & Rabbitt, 2001; Stalvey & Owsley, 2000). For example, one study found that 37 percent of older drivers avoided parallel parking at least some of the time, with 11 percent indicating that they always avoided parallel parking (Baldock et al., 2006). Backing out of a parking space or a driveway can also be dangerous. According to NHTSA (2006) estimates, there

were 183 fatalities and about 6,700 injuries caused by back-up crashes, with older drivers having the highest involvement rate for this type of crash per licensed driver.

Technologies called parking assist (PA) systems have been developed to assist drivers in a number of parking-related tasks, including parallel parking, backing into a perpendicular parking spot, and backing out of a parking space. We include these technologies under the section on collision avoidance systems because they can help prevent collisions with obstacles and cross-traffic when leaving a parking space. However, these systems are also designed to make parking easier and less stressful. Here we review three general types of systems: backup cameras and obstacle warning alerts; cross-traffic alerts; and semi-autonomous parallel parking.

Systems designed to help drivers back up typically include rear cameras that could show the driver the scene behind the vehicle on an in-vehicle video display. These systems can also include enhancements overlaid on the video output that, for example, show graphically the location where a vehicle will end up given the current direction of the front wheels. Some systems, either independently or in conjunction with a camera, provide alerts about obstacles behind the vehicle. Several studies have addressed the use, effectiveness, and perceptions of these systems. One study investigating glance behavior found that people of all ages rarely (8-20 percent) looked at backup camera displays before backing up, but nearly one-half would look at the display after they were presented with an obstacle detection alert (Hurwitz et al., 2010). A naturalistic driving study of 37 drivers (age 25-60) of vehicles equipped with a rear camera (with and without obstacle detection) revealed that drivers look at rearview video displays during backing maneuvers at least some of the time, with approximately 10-14 percent of glances going to the display while backing. In addition, no evidence was found that driver's backing behavior (i.e. speed and acceleration) was influenced by this display. (Mazzae, Barickman, Baldwin, & Ranney, 2008).

An experimental study of a backup assistance system that utilized rear video, obstacle detection, and auditory/visual information on distance to rear obstacles tested a number of use-measures in a set of parking/backup scenarios with 32 drivers who were age 45 and older (McLaughlin, Hankey, Green, & Kiefer, 2003). The study found that: when compared to no backup system: participants parallel parked closer to the curb (8 cm on average); for backing into a perpendicular parking space, participants parked significantly closer to the back of the space; and participants were significantly better at aligning a trailer hitch to a trailer. Some studies have investigated the ability of systems with obstacle detection (with and without a rear camera) to prevent a collision with an obstacle (usually a traffic cone) placed behind the vehicle by an experimenter without the knowledge of the participant (Hurwitz et al., 2010; Llaneras, Neurauter, & Green, 2011; Mazzae et al., 2008; McLaughlin et al., 2003). These studies have found high rates of hitting the obstacle (over 80 percent). However, when glance behavior was analyzed, only a small minority of drivers hit the obstacle if they had looked at the rearview display. Finally, experiences and impressions with backup assistance systems were collected in several studies from drivers who had these systems on their own vehicles. A recent study in the US collected subjective data from older drivers who owned vehicles equipped with backup obstacle detection systems, some which also provided distance-to-obstacle information (Cicchino, Eichelberger, & McCartt, 2015). This study found that: nearly all drivers never turned the system off and received warnings at least once a week; 56 percent reported that they had heard an alert and noticed an obstacle behind their vehicle for which they were previously unaware; 30 percent

reported that the system often provides alerts when there was nothing behind the vehicle; 95 percent reported that they would want the system in their next vehicle; 55 percent reported that the system relieved stress; and 1 percent reported that the system was distracting. Other studies that have investigated older drivers' impressions of backup assistance systems have found that: there is some confusion about how the systems operate; people thought the system would help them avoid crashes; and systems that included both a rear camera and an obstacle warning were more highly regarded (AAAFTS, 2008; Hurwitz et al., 2010; McLaughlin et al., 2003; Mazzae et al., 2008).

A similar type of parking assist system utilizes camera and sensor technology to help identify the presence of cross-traffic and alerts the driver when he or she is backing out of a parking space and cross-traffic is present. In some cases, the system will brake automatically when cross-traffic is detected (see e.g., Seto et al., 2012). A US study in Massachusetts investigated the effects of a cross-traffic alert system in response to real vehicle encroachment with 42 drivers (one-third of whom were age 61-68; Reimer, Mehler, & Coughlin, 2010). The study found that when compared to not using the system, participants experienced slightly but not significantly lower stress levels as measured by changes in heart rate. All participants using the system stopped when cross-traffic was approaching compared to 71 percent who stopped appropriately when not using the system. The study also reported that there were false alarms on about 5 percent of trials. Subjective ratings from this study showed that 79% of participants reported that the system made them safer while backing up and 67% reported that the system reduced the stress associated with backing up. A national study of 210 owners (one-third of whom were age 61 and older) of vehicles equipped with a cross-traffic warning system answered questions about the system (Cicchino & McCartt, 2014). The study found that: the systems were turned on in nearly all vehicles (95 percent) and nearly all drivers had experienced alerts from the system; three-fourths of drivers reported that they were always alerted when cross-traffic was present; 34 percent reported getting unnecessary alerts, primarily in bad weather or when there were stationary objects off to the side; 75 percent thought the system was useful for backing up; and most reported no changes in their backing up behavior in response to the system.

A third type of parking assist system (sometimes called semi-autonomous parking assist) takes over the steering component of maneuvering into a parallel parking space. Studies testing these types of systems in real-world settings with middle-age and older drivers have found that use of the system: reduced mental workload when parking (Tachibana, 2011; Totzke Mühlbacher, & Krüger, 2010); reduced stress as measured by a reduction in heart rate (Reimer, Mehler, & Coughlin, 2010); improved parking behavior as measured by a number of factors (Reimer, Mehler, & Coughlin, 2010; Totzke, Jessberger, Mühlbacher, & Krüger, 2011); rated more positively and might transfer learning so that parking will be improved even when the system is not being used (Kawabata et al., 2008; Reimer, Mehler, & Coughlin, 2010; Totzke et al., 2011).

Intersection Assistance

As discussed previously, negotiating intersections poses a particular challenge for older drivers and this segment of the population is overrepresented in multiple-vehicle crashes at intersections (see Figure 2). Technologies designed to help drivers safely move through intersections have great potential for reducing crashes and the related injuries and deaths.

A number of technologies, collectively called intersection assist (IA) systems (also called intersection warning/decision-support systems, in-vehicle signage systems, and gap-acceptance advisors) have been developed or are in development (see e.g., Band & Perel, 2007; Bougler et al., 2005; Caird et al., 2006; Rusch et al., 2014). These technologies use various combinations of location information, digital map and geographic information system data, infrastructure data, and sensors to determine an approaching intersection and its characteristics and the location and speed of traffic in or approaching the intersection. Depending on the system, information is provided to the driver to help him or her make decisions about negotiating the intersection. This information can simply be appropriate signage displayed inside the vehicle, warnings about disobeying a traffic control device, and/or advice about appropriate gaps for making turns and travelling through intersections where cross-traffic does not stop. While intersection assist systems are not generally available in production vehicles, one would expect with the proliferation of research on connected vehicles that these technologies may become more common.

The systems researched in the current literature are mainly those that rely solely on in-vehicle sensors and data or exist only in a simulation. In-vehicle signage provides several potential benefits including: signs may be easier to locate and understand if they are displayed on an in-vehicle interface; visual signage can be supplemented with auditory information; and additional information can be added such as an indication of the right-of-way for the driver. A simulator study in Germany provided 50 drivers (25 of whom were age 50-78) with right-of-way and traffic volume information about upcoming intersections as they drove through a road network with and without the IA system operational (Ziefle, Pappachan, Jakobs, & Wallentowitz, 2008). The study found that while using the system, all drivers approached intersections more slowly and the effect was greater for the older drivers. As compared to younger drivers, a larger proportion (80 percent versus 45 percent) of the older drivers rated the system as useful. A study in Canada utilized 24 participants (one-half of whom were age 65-76) to investigate the effects of in-vehicle signage (presence of traffic lights) on a number of behavioral measures (Caird et al., 2006). The study found that drivers of all age groups stopped more often at intersections when in-vehicle signs were presented, but older drivers were less likely to do so. Drivers of all ages also tended to approach intersections more slowly in the presence of in-vehicle signage. A study in the Netherlands assessed an IA system that told drivers the right-of-way at upcoming intersections (Davidse, Hagenzieker, Wolffelaar, & Brouwer, 2009). This simulator study included 33 drivers age 70-88. The results showed that when using the IA system, drivers approached intersections more slowly, were more likely to yield appropriately, and were less likely to enter one-way streets in the wrong direction. While older participants were mixed on whether they thought the messages were timed appropriately, nearly all could hear the messages well, and about one-third stated they would want the system in their car.

A simulator study in Iowa assessed the effects of an IA system that determined if a driver was about to disobey a traffic control device (TCD; either running a stop sign or proceeding into an intersection during a "red" light) and provided him or her with a warning (Marshall, Wallace, Torner, & Leeds, 2010, 2011). The study included 36 participants—one-third of whom were healthy and age 65 and older and one-third of whom were age 65 and older and deemed to have declines in driving abilities. Participants completed a 14-20 minute simulated drive while encountering several TCDs under varying conditions of visibility and distraction. If the system determined that the driver was about to violate a TCD, he or she

received a combined visual, auditory, and haptic alert. One-half of the participants experienced the IA system. The results showed that participants using the system had significantly fewer violations of the TCD. At-risk older drivers showed a greater benefit than other groups, but this trend was not significant. Participants who used the system thought it would improve safety, functioned well, and would want the system in their vehicle.

Several IA systems that provide advice on gap acceptance have been developed and assessed in simulator studies utilizing older adults. Because these systems vary greatly in the type and modality of information, a description of each system is beyond the scope of this review. However, all of the systems develop estimates of safe and unsafe gaps in traffic and convey this information to drivers. Collectively, the evaluation of these IA systems with older drivers showed: significantly larger gaps were accepted by all drivers and the variability in gap acceptance decreased; older drivers were more likely to fully-stop at stop-sign controlled intersections when compared to younger drivers; older drivers adopted a more conservative driving style; these systems do not increase distraction; older drivers crossed intersections faster than younger drivers in some studies and more slowly in others; and the systems had no significant effect on crashes, noting that crashes even in simulated driving were very infrequent (Becic, Manser, Creaser, & Donath, 2012; Becic, Manser, Drucker, & Donath, 2013; Creaser, Rakauskas, Ward, & Laberge, 2007; Davidse, Hagenzieker, Wolffelaar, & Brouwer, 2009; Dotzauer, Caljouw, de Waard, & Brouwer, 2013; Dotzauer, de Waard, Caljouw, Pöhler, & Brouwer, 2014; Rusch, Schall, Lee, Dawson, & Rizzo, 2014).

Merging Assistance

Merging onto a freeway can be demanding, stressful, and dangerous, especially for older drivers. Analyses of US "changing lanes/merging" crash data by age group show sharp increases in crash involvement ratios after age 69, with the steepest increases found for multiple-lane roadways (Stutts, Martell, & Staplin, 2009). To address these issues, systems are being developed, called Merging Assist (MA) systems, to help drivers safely and efficiently merge onto a freeway. These systems take advantage of location information, onboard sensors and data, and vehicle-to-vehicle connectivity to provide information to the driver who is merging and to the drivers who are in the travel lane into which a vehicle is merging (Amano & Tsugawa, 2010; Sakakibara & Tsugawa, 2013; Hayat, Park, & Smith, 2014). MA systems will ultimately be designed to provide advisory messages or take partial control of vehicles to assist in the merging maneuver.

A study in Germany evaluated the driver response to a simulated MA system with participants who were age 22-63 years (Maag & Mark, 2012). One unique aspect of this study was that the simulation utilized a "multi-driver" method where both the driver of the merging vehicle and the driver of the vehicle in the through lane were incorporated into the simulation as in a multi-player game. The simulated MA system advised the merging driver about appropriate gaps. The study found that: merging drivers judged gaps as appropriate whereas drivers in the through lane tended to judge the same gap as too small for merging; the MA system reduced feelings of anger reported by the merging driver; drivers nearly always chose the recommended gap for merging; and the system had no effect on merging safety.

A Japanese study utilized a MA system that gave alerts to drivers about potential merging conflicts (Hatakenaka et al., 2008). The system was installed in test vehicles that participants (age 20-60) drove past specific locations in which the roadway infrastructure was installed with infrastructure-to-vehicle communications. The study showed that nearly all participants reported understanding the messages; a large majority thought the messages were timed appropriately; and most participants reported driving more cautiously, paying greater attention to the merge lane, and that the system was useful.

A demonstration MA system was developed and tested by the University of Virginia on a closed course (Hayat, Park, & Smith, 2014). This system was designed specifically to assist drivers in merging onto a freeway by encouraging drivers in the through lane to change lanes when appropriate to create larger gaps for merging and by providing merging advice (speed and lane change recommendations) to drivers of vehicles that were merging. Trials were conducted on a closed course varying gap sizes and the advisory types using 25 participants (no ages given). The preliminary results showed that as the gap size was reduced, driver compliance with the advisories was less frequent. Questionnaire data indicated that drivers reported they would be more likely to follow recommendations in light traffic conditions, unfamiliar areas, and scenarios where a clear conflict was perceived. This study is ongoing.

In-Vehicle Information Systems

In-vehicle information system (IVIS) technologies are designed to provide a driver with information that he or she can use to make better driving decisions (Simões & Pereira, 2009). Generally this information is not intended for the second-by-second operation of the vehicle but rather for improving strategic driving decisions over a longer time-frame, such as deciding where to make a turn or preparing for upcoming traffic congestion. Here we review three IVISs—navigation assistance, congestion warnings, and intelligent speed adaptation.

Navigation Assistance

Navigation assistance (NA) systems combine global positioning system (GPS) vehicle location information with digital map data to provide drivers with turn-by-turn, instructions (visual and auditory) to locations as they drive. Some systems can utilize cellular or other communication means to obtain real-time traffic volume information and adjust guidance information to avoid traffic congestion (see e.g., Kostyniuk et al., 1997). Nomadic NA systems are widely available as an aftermarket product and most smartphones have applications that provide NA system functionality. This review, however, is limited to synthesizing the research on manufacturer-installed NA systems.

Given the difficulty older drivers have in wayfinding (see e.g., Bryden, Charlton, Oxley, & Lowndes, 2013), particularly in unfamiliar areas, NA systems have been cited as being particularly helpful for older drivers (AAAFTS, 2008; Baldwin, 2002; Band & Perel, 2007; Eby & Kostyniuk, 1998; 1999; Eby & Molnar, 1999; Kostyniuk, Streff, & Eby, 1997). Several studies have assessed older drivers' use and perceptions of NA systems under actual and simulated driving conditions. Collectively these studies showed that older drivers: used NA systems frequently; reported only minimal distraction, but more than

reported by younger drivers; traveled to places they would not have gone to without the system; more frequently travelled during times and on roadways that they would normally avoid; reported increased feelings of safety, confidence, attentiveness, and relaxation when using NA systems; tended to still bring paper maps along in case the NA system failed; took longer and had more difficulty learning to use NA systems; were more likely to have learned how to use the system from a friend or family member; had more difficulty than younger drivers reading the displays; more frequently used the system with a "co-navigator" passenger than reported by younger drivers; some reported feeling that the NA system was more like a human co-navigator than a technological device; reported higher preferences for verbal turn-by-turn instructions; and would not buy a system targeted to "old" people (Chan & Rose, 2002; Dingus et al., 1997; Eby & Kostyniuk, 1998; 1999; Eby & Molnar, 1999; Emmerson, Guo, Blythe, Namedeo, & Edwards, 2013; Kessler et al., 2012; Kostyniuk, Eby, Christoff, & Hopp, 1997; Novotný & Bouchner, 2011; Oxley, Barham, & Ayala, 1995; Vrkljan & Polgar, 2007; Zhang, Wang, & Dong, 2012).

Congestion Warning

Work zones, accident zones, and other non-recurrent congestion scenarios increase the risk of crashes primarily due to drivers approaching these zones with inadequate forewarning. Work zones are estimated to be a contributing factor in about 22 percent of freeway crashes and older drivers have been found to be overrepresented in these crashes (see e.g., Heaslip, Collura, & Knodler, 2009). This is consistent with self-reports by older drivers (age 65-89) related to concerns about congestion and construction zones while driving on limited access roads such as freeways (Alicandri, 1998).

Technologies, called congestion warning (CW) systems, have been developed or are in development that utilize communication with the infrastructure and/or other vehicles and vehicle-location information that warns the driver about the upcoming congestion (e.g., Brookhuis et al., 2008). Many of these systems operate on the roadside only, others link with nomadic devices, while still others operate as an in-vehicle technology (Cooner & Wiles, 2006; Nowakowski et al., 2011).

Several simulator studies have investigated the use and potential benefits of CW systems, most of which have not included older drivers. Collectively the studies have found that when compared to not using a CW system, these systems: decreased mental workload; led drivers to start decelerating sooner; reduced maximum decelerations and hard braking; did not influence overall driving speed; decreased mean headways before traffic congestion incidents; were generally considered acceptable to drivers, but not overwhelmingly so; led to higher perceived safety when approaching a congestion; and the rated usefulness and satisfaction of CW systems was positive (Brookhuis et al., 2008; Popiv et al., 2010; Totzke, Naujoks, Mühlbacher, & Krüger, 2011; van Driel, Hoedemaker, & Arem, 2007).

Finally, in a field operational study (Nowakowski et al., 2011, 2013), 24 commuters (age 23-61) in San Francisco, California used specially instrumented test vehicles for their normal driving for 2 weeks. Installed in the vehicles was an experimental CW system that communicated with roadside sensors and utilized a central database and computing facility that determined when the vehicle approached specific congestion-related test sites. The system warned the driver if congestion was present at the test sites. The system was turned off for the first week of driving and activated for the second week. Several objective and

subjective measures were gathered in the study for 405 baseline incidents and 406 cases in which the CW system provided an alert. The study found: a high false alarm rate; smoother deceleration when using the CW system; a small but significant change in the mean and mean-peak decelerations between baseline and system use; that about one-half of the participants rated the alerts as good (13 percent rated them as bad); and that 41 percent thought the timing of the alert was good, 48 percent thought they were early, and 11 percent thought they were late.

Intelligent Speed Adaptation

It is well-established that speeding is a causative factor in motor vehicle crashes (e.g., Liu, Chen, Subramanian, & Utter, 2005; McGwin & Brown, 1999; Siskind et al., 2011), with about 30 percent of fatal crashes in the US attributed to speeding (NHTSA, 2012). Studies, however, have shown that speeding is an infrequent behavior among older adults and those with age-related medical conditions (Charlton et al., 2006; Eby et al., 2012). Older adults are also underrepresented in speed-related traffic crashes (Langford & Koppel, 2006; McGwin & Brown, 1999; Planek & Fowler, 1971; Stamatidis, 1996).

In an effort to curtail speeding and the resulting crashes, technologies, called intelligent speed adaptation (ISA) systems, have been developed to encourage people to drive at the set speed limits. ISA systems use vehicle location information, driving speed, and an underlying database to determine the relationship between the vehicle speed and the speed limit for the road on which a driver is travelling (Marchau, van Nes, Walta, & Marsink, 2010). If the driver is speeding, the systems are designed to give in-vehicle feedback (visual, auditory, and/or haptic) to the driver. Some systems can also take over partial control of the vehicle and decrease vehicle velocity to the posted speed limit. Some systems have also been linked with auto-enforcement units that can deliver fines and/or rewards. Several studies have concluded that if ISA systems were in wide-spread use, there would be a significant decrease in crashes, injuries, and the associated costs (see e.g., Carsten & Tate, 2005; Doecke & Wooley, 2011; Lai, Carsten, & Tate, 2012).

Simulator studies on the effects of ISA on the driving behaviors and perceptions of participants have generally not included older adults. These studies have found that: ISA systems that simply inform drivers that they are speeding do not change speeding or passing behavior; ISA systems that took over partial control of the vehicle reduced speeding, decreased following distance in some studies, and decreased passing behavior frequency; both types of systems were judged as useful and would improve road safety; and neither system was judged as satisfactory or desirable (Comte, 2000; Jamson, 2006; Jamson, Chorlton, & Carsten, 2012; Spyropoulou, Karlaftis, & Reed, 2014). A simulator study in Japan compared 15 young drivers to 16 older drivers (no ages given) on use of ISA systems and reactions to various types of ISA advisories (Ando et al., 2014). This study found that the advisories had a larger effect on young drivers due to the fact that younger drivers drove faster without the ISA system.

The effects of ISA system on driver behavior and attitudes have been investigated in real traffic in a number of studies, some of which included older adults (Lai & Carsten, 2012; Lai, Hjälm Dahl, Chorlton, & Wiklund, 2010; Reagan & Bliss, 2013; Regan et al., 2006; Vlassenroot et al., 2007; Wall, Cuenca, Creef, & Barnes, 2013). When compared to not using a system, use of an ISA system that actively slowed the vehicle to prevent speeding

shows that: the system significantly reduced excessive speeding; speed profiles were closer to posted speed limits; the system was overridden (turned off) by the driver most often on high speed roads (16 percent of the time for 70 mph roads) followed by the lowest speed roads (13 percent of the time for 20 mph roads); speeding was frequent when the system was overridden; and the longer the system was used the more frequently the system was overridden (Lai & Carsten, 2012; Lai et al., 2010).

An ISA system in the US that provided auditory and visual advisories about speeding (differentiating between "moderate" and "egregious" speeding) was tested with 50 participants (age 25-35) in real traffic over a 1-month period (Reagan et al., 2013; Reagan & Bliss, 2013). The study included three groups. One was a control group of 10 drivers who drove without the ISA system operating. One group drove with the system activated (feedback only). The final group of participants drove with the ISA activated but also was given a monetary incentive to drive within the speed limit. This latter group of participants were told that they could earn up to \$25 at the end of the study, with the amount decreasing slightly with each instance of speeding (-\$0.03 for moderate and -\$0.06 for egregious speeding). The study found that: there was a moderate reduction in speeding with the feedback only and a significant reduction in speeding with the incentive; mental workload increased for both systems; the system was rated positively for reliability, predictability, accuracy, agreeableness, trustworthiness, and acceptability; participants found the auditory component of the system annoying; and participants would not pay to have the system in their vehicle.

Questionnaire studies in several countries have explored the general public's opinion of ISA systems, including older adults (Chorlton, Hess, Jamson, & Wardman, 2012; Eriksson & Bjørnskaug, 2012; Garvill, Marell, & Westin, 2003; Vlassenroot, Brookhuis, Marchau, & Witlox, 2010; Warner, Özkan, & Lajunen, 2010). Collectively, these studies have found: agreement that speeding is an important traffic safety issue; limited awareness of or experience with ISA systems; moderate support for a voluntary ISA system that provided feedback only; low support for ISA systems that actively control speed; moderate support for ISA systems being used only on certain roadways or in the vehicles of frequent speeders; and that drivers who were frequent speed violators were less favorable of ISA systems.

Other Systems

The final category of advanced in-vehicle technologies includes those that are not strictly collision avoidance or IVISs. Many of these systems can improve safety but may also function as a means to make driving easier or more comfortable. Here we review the following systems: adaptive cruise control; automatic crash notification; night vision enhancement; adaptive headlights; voice activated control; and drowsiness/fatigue warnings.

Adaptive Cruise Control

One of the earliest advanced in-vehicle technologies to be developed was adaptive cruise control (ACC; de Winter, Happee, Martens, & Stanton, 2014). Regular cruise control requires the driver to brake if he or she gets too close to a forward vehicle. ACC systems, on the other hand, allow a driver to set a preferred headway, and a forward mounted sensor

detects traffic in front of the vehicle, calculates the current headway, and interfaces with the throttle to change the vehicle's speed to maintain a certain headway (Fancher et al., 1998; Hoedemaeker & Brookhuis, 1998). ACC systems are designed primarily to make driving easier and as such are considered comfort and convenience technologies.

A study in England investigated behaviors and perceptions of 110 participants (age 18-73) using an ACC system in a simulator (Stanton & Young, 2005). Participants drove simulated routes that varied in the levels of traffic with and without the ACC system activated. The study found that as compared to driving without the ACC system, use of the system decreased workload, stress, and situational awareness; reported frustration was higher for the ACC system in high levels of traffic; and there was no effect on locus of control or trust. The authors concluded that the ACC system served its purpose as a comfort and convenience technology, but cautioned that future designs should attempt to provide better situational awareness.

Some authors have argued that the ACC might have a negative impact on safety, primarily through a reduction in situational awareness, risk compensation, and a lack of understanding of the system's functional limitations (de Winter et al., 2014; Hoedemaeker & Brookhuis, 1998; Piccinini et al., 2014, 2015; Rajaonah, Anceaux, & Vienne, 2006; Seppelt & Lee, 2007; Xiong et al., 2012). For example, a simulator study of 38 participants (age 25-60) who drove with and without ACC found that when driving with ACC, participants drove faster, with smaller minimum headways, and applied larger force to the brakes (Hoedemaeker & Brookhuis, 1998). A study in Portugal compared drivers who were experienced users of ACC to people who were not (age 33-61) while driving in a simulator with and without ACC (Piccinini et al., 2015). During the driving trials, participants were presented with a vehicle that was stopped on the roadway in front of them requiring them to brake to avoid a collision (note that ACC is not designed to automatically stop the vehicle in this situation, as the systems are not forward collision warning systems). The study found that both experienced and inexperienced ACC users had increased risk of hitting the stopped vehicle as compared to not using ACC. Data revealed that many participants in both groups were not fully aware of how ACC would react to a stopped vehicle. This result is supported by studies that have asked users (mean age of 54-55) about limitations of their ACC system (Bato & Boyle, 2011; Dickie & Boyle, 2009).

A study of an ACC system installed in an instrumented vehicle used on a test-track reported similar concerns (Rudin-Brown & Parker, 2004). This study investigated how ACC influenced driving among 18 drivers age 21-34. Participants drove an ACC-equipped vehicle behind a "surrogate" lead vehicle, while performing non-driving tasks. The study found that use of ACC reduced driver workload and increased response times in a hazard detection task. Drivers trusted the system even after a simulated failure, a condition in which trust should have been reduced. Drivers also had greater lane position deviation when using ACC. This latter result suggests that less attention was being paid to steering when using the system, but drivers were not crossing over lane boundaries. The authors suggested that use of ACC systems should be coupled with training on situational awareness and on how the systems operate.

The safety concerns of ACC have not been fully borne out in field tests, where people drive as they normally would in natural driving conditions. Fancher et al. (1998) furnished 108 participants (one-third age 60-70) with an ACC-equipped vehicle for their own use for up to

5 weeks. Collectively, these participants used ACC for more than 35,000 miles. Participants could turn the system on or off at any time, thereby self-selecting the traffic conditions under which the system was tested. Overall, participants used the ACC system in more than 50 percent of their travel, primarily on limited access freeways. The older participants used the system the most frequently. The study found significantly higher deceleration rates while using ACC, suggesting greater intervention was required to avoid a collision. However, the authors noted that participants appeared to be using the system in a "supervisory" role, and waited to see if the system would resolve a forward conflict, with attention being drawn to the potential conflict by the deceleration from the ACC. If the system could not resolve the conflict quickly, then the driver applied the brake. The authors reported no crashes during the period of ACC use and, based on several analyses, concluded that ACC was safe. Participants overwhelmingly were comfortable with the system and found it highly attractive. Field tests of systems that coupled ACC and FCW technologies, most of which included older driver groups, have been conducted in both the US and Europe (Ervin et al., 2005; Kessler et al., 2012; Rakha, Hankey, Patterson, & van Aerde, 2001) and have also found ACC to be safe and positively received.

A number of studies have investigated the use and perception of ACC systems among people (31 – 50 percent of whom were older drivers, depending on the study) who have an ACC system in their personal vehicle (AAAFTS, 2008; Cicchino & McCartt, 2014; Eichelberger & McCartt, 2014a, 2014b; Strand et al., 2011). These studies have found that: ACC systems were used for a large majority of trips, most frequently on freeways, and older drivers used the system more than younger drivers; on ACC systems in which the headway can be set by the user, older drivers tended to use the largest headway; one-third to one-half reported following vehicle less closely when using ACC; more than 90 percent reported that they did not look away from the road more when using ACC; about 40 percent reported that the ACC system made them a better driver; and about 40 percent erroneously reported that the ACC system would help them avoid a collision with a stopped vehicle in the lane ahead.

Automatic Crash Notification

Getting emergency services personnel to the exact scene of a crash quickly can raise the probability of saving lives and reduce the severity of injury outcomes. Automatic crash notification (ACN) systems (also called mayday systems) employ communication technology that can contact emergency medical services (EMS) personnel automatically within a few seconds after a crash (Hunt, 2002; Williams, 2002). The type of information transmitted to EMS varies depending on the system, but can include GPS location, vehicle information, and in some cases, data about the crash type and/or severity (Champion et al., 2003). ACN systems are usually triggered by an airbag deployment, but other crash sensors can be used (Walker et al., 2010). While not systems designed to impact driving or mobility, ACN systems can aid in saving lives by dispatching emergency assistance earlier than is normally possible.

Several studies have estimated the reduction in fatalities of ACN systems using actual crash data and assumptions about ACN system market penetration. An evaluation in Korea estimated that if all vehicles were equipped with ACN systems, 9-15 percent of crash-fatalities could be prevented on Korean highways (Jeong, Oh, & Lee, 2014). A study in Finland examined an ACN system and concluded that the system prevented 4-8 percent

of road fatalities (Sihvola et al., 2009). Another study estimated the effects of an ACN system employed across the US and reported that such a system could save 2-6 percent of fatalities each year (Clark & Cushing, 2002). Another US study using US data, reported that if an ACN system could notify EMS personnel within 1 minute after a crash, the system could save up to 290 lives each year and reduce fatalities by 1.8 percent within the first 6 hours of a crash (Wu et al., 2013). An Australian study concluded that ACN in that country could prevent up to 10 percent of passenger-vehicle fatalities each year (Lahausse, Fildes, Page, & Fitzharris, 2008). Other studies have also demonstrated the safety benefits and efficacy of ACN systems (Berryman, 2004; Kaniyanthra, Carter, & Preziotti, 2000). No research has directly considered the safety benefits of ACN systems for older drivers, but given the increased likelihood of frailty and fragility in older adulthood, it is logical to propose that ACN systems might have a greater safety benefit for older drivers and passengers.

Night Vision Enhancement

It is well-documented that one self-regulatory behavior engaged in frequently by older adults is avoiding driving at night due to difficulties with seeing at night (Baldock et al., 2006; Charlton et al., 2006; Molnar et al., 2013). When exposure is taken into account, there is some evidence that older drivers have higher nighttime crash rates than drivers in the middle-age group (see e.g., Massie, Campbell, & Williams, 1995; McGwin & Brown, 1999; Stutts & Martell, 1992). Technologies that help drivers see at night, called night vision enhancement (NVE) systems, have been proposed as a potential technology that can help older drivers while driving at night (Band & Perel, 2007). NVE systems are designed to provide drivers with roadway information that is either difficult or impossible for the driver to obtain through direct vision, using infrared cameras to detect pedestrians, animals, signs, and other aspects of the roadway scene, intelligent image process, and video technology. This information is displayed on an in-vehicle video screen (Rumar, 2002). Some systems also include a warning to alert drivers that an object, such as pedestrian, has been detected (Brown, He, Roe, & Schnell, 2010; Hankey, Kiefer, & Gibbons, 2005).

Studies of NVE systems have utilized simulators, closed course test-tracks, and on-the-road studies, some of which included older adult groups of participants (e.g., Druid, 2002; Gish, Shoulson, & Perel, 2002; Gish, Staplin, & Perel, 1999; Ståhl, Oxley, Berntman, & Lind, 1994; Sullivan, Bårgman, Adachi, & Schoettle, 2004; Raytheon Commercial Infrared and ElCAN-Teaxs Optical Technology, 2000). Collectively, these studies have found that: drivers reported that they could intuitively interpret the displays; however, this ability seemed to be reduced when the display was not positioned above the steering wheel; NVE systems increased target detection distance by all drivers and the system only raised driver workload by a small amount; older drivers did not use the NVE system as frequently as younger drivers, possibly because of decreased divided attention capacity; the ability to detect pedestrians increased but only for younger drivers; generally system benefits were greater for younger drivers; older drivers reported being satisfied with NVE system; and older drivers did not think the system would result in a reduction of crashes. The actual safety benefits of NVE systems have not been established. Given that these study results suggest that NVE systems do provide some vision assistance with only small increases in workload, it is possible that they might improve safety for older drivers. More research is needed to establish the extent to which these systems do or do not improve safety for older drivers.

Adaptive Headlights

As another way to improve vision while driving at night, systems have been developed to improve the effectiveness and functioning of the vehicle's headlight system. These technologies, called adaptive headlight (AH) systems, involve a number of systems including ones that turn the highlights in the direction of a curve, automatically dim high-beam headlights in the presence of oncoming traffic, and control the direction and intensity of the headlight beam when opposite traffic is approaching (Band & Perel, 2007). Collectively, AH systems are designed to improve nighttime driving visual capabilities for the driver of a vehicle and to reduce glare disability of drivers in other vehicles. The latter two systems are under development and little literature is available about the use or impacts of these systems.

A number of studies of AH systems that dynamically position the headlights in the direction of curves have been evaluated. Studies that have addressed the safety benefits of AH systems estimate that if fully-implemented in the US light-vehicle fleet, there would be an annual reduction in crashes of 2-5 percent (142,000 crashes per year) and about 2,700 pedestrian-related crashes per year could be prevented (Jermakian, 2011; Mehler et al., 2014b; Sullivan & Flannagan, 2007). Analysis of insurance data for vehicles equipped with AH systems, as compared to those without them, found a 5 to 10 percent decrease in liability claims (IIHS, 2012).

The impacts of AH systems on visibility of objects and pedestrians have been investigated on test-tracks and on the roadway. Sivak et al. (1994) compared an AH system to normal headlights (with 16 subjects, one-half of whom were age 62-72) on pedestrian detection, glare discomfort from the perspective of other drivers encountering the headlights, and thoughts about the systems after 30 kilometer trips in real traffic. The study found that: the AH system improved pedestrian visibility by 14 percent for left-curves and 1 percent for right-curves; discomfort glare was higher for the AH system on left-curves and lower on right-curves; participants thought the headlight movement was not smooth and took too long to return to straight ahead after curves; and there was no overall preference for either the AH or normal headlight systems. A European study included 22 participants (mean age 37) who drove several simulated trips through cities and rural areas over a 6-day period (Jenssen, Bjørkli, Sakshaug, & Moen, 2007). All participants drove baseline trips with and without the AH system and then one-half used the AH system on the remaining trips while the other half used a standard headlight system. The study found no differences in driving patterns between groups or over time, with the exception of speed. All participants drove faster over time and participants using the AH system drove faster at night while in city traffic conditions.

Braitman et al. (2010) assessed the use of and opinions about AH systems among 290 owners of vehicles with such systems (20 percent were age 61 or older). The study found that: 7 percent of owners were not aware that the system was in their vehicle; 18 percent thought the system improved visibility in general; 14 percent thought the system was helpful for negotiating curves; 84 percent reported that there was nothing they disliked about the system; 87 percent preferred the AH system over standard headlights; and 77 percent thought the system improved safety. When asked about changes in driving behaviors while using the system, 40 percent reported that they were more willing to drive

at night and 18 percent reported that they were more willing to drive faster at night. No analyses by age group were presented.

Voice Activated Control

Many advanced technologies, both in-vehicle and nomadic devices that link with in-vehicle technology, require input from the driver. Manual input can lead to various forms of distraction that could increase crash risk (Barón & Green, 2006). Recently, technologies have been developed that utilize speech recognition algorithms that allow the driver to use voice commands to control various technologies such as adjusting the radio, processing email, phone dialing, and entering destinations into a navigation system. While not a self-contained technology, voice activated control (VAC) systems are designed to make interfacing with in-vehicle technologies easier and safer.

VAC systems have been compared to manual control systems in driving simulators on a variety of safety measures in several studies, none of which included older adults as participants (He et al., 2014; Itoh et al., 2004; Jenness et al., 2002; Lee, Caven, Haake, & Brown, 2001; Maciej & Vollrath, 2009; Strayer et al., 2013). These studies reported that: there was lower cognitive distraction for VAC systems than for manual control; both systems impaired driving performance significantly more when compared to driving without using either system; the manual system produced greater safety decrements in driving performance as compared to VAC systems; there was significant cognitive distraction when using VAC systems as compared to not using a VAC system; and reaction time was slower when using a VAC system. These studies suggest that VAC systems were safer than manual control but, as one set of researchers concluded: "Despite the appearance of safety...speech-based interface can distract drivers and undermine driving safety." (Lee et al., 2001, pg. 639).

Test-track and on-road studies have also investigated safety and ease-of-use measures for VAC systems (Chiang, Brooks, & Weir, 2005; Mehler et al., 2014a, 2014b; Neurauter, Hankey, Schalk, & Wallace, 2012; Perez et al., 2011; Ranney, Mazzae, Baldwin, & Salaani, 2007; Reimer et al., 2013; Schreiner, Blanco, & Hankey, 2004; Strayer et al., 2013, 2014). The results of the studies, some of which included older drivers as participants, found that: use of VAC systems in some instances produced significant levels of cognitive distraction; VAC systems had significant safety advantages over manual control systems on several measures; VAC systems were easier to use than manual entry; VAC systems as compared to manual entry systems were fast to use in some cases and slower in others; VAC systems improved driver performance when compared to manual systems; while using a VAC system, driving performance significantly declined while interacting with a range of in-vehicle technologies; and drivers liked VAC systems and would want them in their next vehicle. Results were generally the same among the older participants in these studies except: that older adults had greater difficulty using the VAC systems; and they experienced greater distraction and greater decrements in driving performance as compared to younger drivers.

Drowsiness/Fatigue Warnings

A recent analysis of the US National Automotive Sampling System Crashworthiness Data System (NASS-CDS) investigated the prevalence of drowsy driving in motor vehicle crashes

from 2009-2013 (Tefft, 2014). The study estimated that drowsy driving was involved in 21 percent of fatal crashes, 13 percent of crashes requiring a hospitalization, 7 percent of crashes involving minor injuries, and 6 percent of property-damage only crashes. This translates into about 328,000 crashes involving a drowsy driver per year. Studies that have considered drowsy driving crashes by age group showed that they decrease in frequency with age, with estimates ranging from about 1 to 5 percent of older driver crashes being related to drowsy driving (Stutts, Martell, & Staplin, 2009; McGwin & Brown, 1999). According to data from the Centers for Disease Control and Prevention's 2009-2010 Behavioral Risk Factor Surveillance System questionnaire, 1.7 percent of adults age 65 and older reported having fallen asleep while driving in the past 30 days (Wheaton et al., 2013).

To address the problem of drowsy driving, a number of approaches have been taken to develop technologies, called drowsiness (fatigue) warning (DW) systems, which can automatically detect drowsiness or fatigue and provide an alert. As discussed by Balkin et al. (2011), in-vehicle approaches to DW systems have used sensors or video that detect brain wave activity, ocular measures such as eye closure, facial features, head motions, and driving performance measures. The number of different systems is too large to review each here, but reviews of several demonstration systems in terms of their ability to accurately detect drowsiness have concluded that: many systems, particularly those based on eye closure data, are fairly robust for detecting drowsiness, they are much less robust for detecting levels of drowsiness; the systems generate fairly high rates of false alarms (10-14 percent); and brain-wave-based systems (EEG) require the driver to wear sensors while others require personal calibration—features that are likely not practical for general use (Balkin et al., 2011; Horberry, Hartley, Krueger, & Mabbott, 2001; Williamson & Chamberlain, 2005).

A prototype DW system, based on detection of eye closure, was tested in actual driving conditions among a group of 102 commercial vehicle drivers with an average age of 40 (Blanco et al., 2009). Drivers participated for approximately 3-4 months, with the first 40 days serving as a baseline with the system turned off. About one-quarter of the participants served as a control group with no DW system activated for the entire study. The study found: no clear effect of the DW system on driver performance in traffic conflict situations; no significant difference on the number of safety critical events with or without the DW system; that drivers with negative opinions of the system tended to have a lower rate of valid alerts while drivers who were favorable to the system had an increase in safety benefits; and that despite the fact that many drivers agreed that the system could lead to increased safety, many commented on the system's functional limitations. Development of these systems continue (see e.g., Bowman et al., 2012; Golz et al., 2010).

Some systems that are similar to drowsy driver alerts have been available in vehicles for some time. These systems, usually called driver state warnings or driver alert controls, detect lane deviations and present warnings to the driver if the system has determined that the driver may not be alert. Surveys and focus groups of drivers (a large portion of which were older drivers) of vehicles with these systems installed have found that: most of the owners had received a warning and 80 percent thought that they were alert when they were warned; there was some confusion about what the warning indicated; more than one-half ignored the alert; 13 percent said they paid more attention to driving after receiving the warning; and a small number deactivated the system (Eichelberger & McCartt, 2014b; Strand et al., 2011).

Discussion

Research findings on 16 advanced in-vehicle technologies were reviewed with regard to how older drivers use and think about these technologies, and how the technologies can and do influence behaviors and safety outcomes. The results are summarized in Table 2. The Table also contains our conclusions about the potential level of benefit that older drivers might experience by using each of these technologies. Many of these technologies are available today in vehicles, while some of the technologies are under development and expected to be available in the near future.

Lane departure warning/mitigation (LDW) systems

We conclude that LDW systems could have great value for older drivers, particularly for those who are taking medications that can produce drowsiness. These systems could also provide great value for older drivers when taking long trips that could produce fatigue. Unfortunately, more real-world data are needed to fully understand the safety benefits of LDW for older drivers. Further, for these systems to be accepted by older adults they will need to be operationally robust (i.e., work under most driving conditions), the number of false alarms will need to be small, and drivers should be able to selectively use the system under the conditions that they choose, allowing them to turn off the system in bad weather or on roads that have poor lane markings.

Curve speed warning (CSW) systems

The limited research shows that older drivers like CSW systems, and in experimental tests, use of the systems resulted in older drivers taking turns at speeds that were closer to the recommended speed. However, studies that have assessed the impact of CSW systems on older adults' driving behaviors under normal driving conditions have found no change in driving behaviors, despite the finding that older drivers liked CSW systems. Thus, we conclude that CSW systems provide minimal value for older drivers.

Forward collision warning/mitigation (FCW) systems

There is overwhelming evidence attesting to the safety benefits of FCW systems for all drivers and for older drivers specifically. For older adults, the evidence shows that FCW systems can help prevent crashes without causing a negative impact on other behaviors such as increased speeding or more frequent engagement in non-driving tasks. Older drivers who have used these systems under normal driving conditions are favorable toward them and a large majority reported that such systems had prevented crashes. There is some concern about false alarms among older adults that should be addressed in future designs. We conclude that FCW systems could have great value for older drivers.

Table 2: Summary Information on Technologies (below)

Technology	Use	Perceptions	Outcomes	Overall Value for Older Drivers
Lane Departure Warning/ Mitigation	<ul style="list-style-type: none"> Frequent use However, up to 22% do not use system when available 	<ul style="list-style-type: none"> Considered helpful/useful, especially for long trips Concerns about getting alerts soon enough Small but non-trivial false alarm rates, usually in situations where lane markings poor/covered Large percentage report wanting system in next vehicle 	<ul style="list-style-type: none"> Potential crash reduction of up to 30% Better lane keeping when distracted Increased use of turn signals Fewer lane excursions Reduced stress 	Moderate
Curve Speed Warning	<ul style="list-style-type: none"> No information identified in literature 	<ul style="list-style-type: none"> Satisfaction rated as neutral Some utility recognized 	<ul style="list-style-type: none"> No significant change in objective curve-taking behaviors Some evidence of more appropriate speeds at night on closed course 	Low
Forward Collision Warning/ Mitigation	<ul style="list-style-type: none"> Nearly all drivers always keep the system on Older drivers pick longer headways 	<ul style="list-style-type: none"> System rated positively Some concerns about false alarms 	<ul style="list-style-type: none"> Faster reaction times to forward threats Potential crash reduction of up to 20% Helps prevent crashes Little negative behavior adaptation 	High
Blind Spot Warning	<ul style="list-style-type: none"> Frequent use Use of system led to less frequent signal use 	<ul style="list-style-type: none"> Concerns about false alarms in bad weather Some reported it to be distracting Overconfidence in system 	<ul style="list-style-type: none"> Prevents crashes Less frequent turning of head to check blind spot in 1/3 of participants Increased situational awareness 	Moderate (High when coupled with other collision warning systems)
Parking Assist: rearview display	<ul style="list-style-type: none"> Most drivers always keep system on 10-14% of glances go to rearview display while backing Warnings received at least once per week 	<ul style="list-style-type: none"> 95% want system in next vehicle 30% report frequent unnecessary alerts when there is nothing behind vehicle 	<ul style="list-style-type: none"> Helps drivers notice obstacles behind them Improves ability to fit squarely in parking spaces 55% reported system relieves stress Combining backup video display with obstacle detection warnings enhances benefit 	High
Parking Assist: cross traffic warning	<ul style="list-style-type: none"> All drivers turn system on All experience alerts 	<ul style="list-style-type: none"> Considered useful Up to one-third report unnecessary alerts, mostly in bad weather or with stationary objects off to the side Up to 15% report failed alerts at least once, when another vehicle is approaching from behind very 	<ul style="list-style-type: none"> Helps prevent collisions when backing up No changes in backing up behaviors 	High

		<ul style="list-style-type: none"> quickly Reduces feelings of stress Increases feelings of safety while backing up 		
Parking Assist: semi-autonomous parking assistance	<ul style="list-style-type: none"> No information identified in literature 	<ul style="list-style-type: none"> Positive ratings 	<ul style="list-style-type: none"> Reduced mental workload Reduced stress Improved parking behavior Improved parking without the system 	High
Intersection Assistance	<ul style="list-style-type: none"> Actual system under development; only simulated systems have been tested 	<ul style="list-style-type: none"> Positively regarded 	<ul style="list-style-type: none"> Potential benefit of providing intersection signage on an in-vehicle display Potential benefit of providing gap-acceptance advice 	Too early to assess
Merging Assistance	<ul style="list-style-type: none"> Actual system under development; only simulated systems have been tested Little data with older drivers 	<ul style="list-style-type: none"> Drivers report being more likely to follow advice in light traffic conditions, unfamiliar areas, and scenarios where clear conflict is perceived 	<ul style="list-style-type: none"> Some evidence of safer merging More cautious driving 	Too early to assess
Navigation Assistance	<ul style="list-style-type: none"> Frequent use Take longer and have more difficulty than younger drivers learning to use system Have more difficulty than younger drivers reading displays More frequently use system with a "co-navigator" passenger 	<ul style="list-style-type: none"> Highly regarded 	<ul style="list-style-type: none"> Particularly helpful in wayfinding More frequent travel during times and on roadways that would normally be avoided Increased feelings of safety, confidence, attentiveness, and relaxation Only minimal distraction reported 	High
Congestion Warning	<ul style="list-style-type: none"> System in development; will likely benefit from future connected vehicle technologies 	<ul style="list-style-type: none"> High false alarm rate System rated as neutral 	<ul style="list-style-type: none"> Earlier and smoother deceleration entering into congested traffic Increased mental workload 	Too early to assess
Intelligent Speed Adaptation	<ul style="list-style-type: none"> Limited awareness of or experience with system 	<ul style="list-style-type: none"> Not positively received, especially for active systems 	<ul style="list-style-type: none"> No impact on speeding behaviors unless system actively slows down speeding vehicle 	Low
Adaptive Cruise Control	<ul style="list-style-type: none"> Frequent use Full understanding lacking about situations under which system does and does not operate 	<ul style="list-style-type: none"> System valued for comfort and convenience Overconfidence in system 	<ul style="list-style-type: none"> Lower levels of stress and workload Reduced situational awareness Late braking for critical events 	Moderate (After proper training and/or if linked with FCW)
Automatic Crash Notification	<ul style="list-style-type: none"> Does not require user input 	<ul style="list-style-type: none"> No information identified in literature 	<ul style="list-style-type: none"> High potential for fatal crash reduction 	High
Night Vision Enhancement	<ul style="list-style-type: none"> Used less frequently than by younger drivers 	<ul style="list-style-type: none"> Satisfaction with system System not considered to result in 	<ul style="list-style-type: none"> Provides some vision assistance with only small increases in workload 	Low

		crash reduction	<ul style="list-style-type: none"> Increased target detection distance System benefits greater for younger drivers 	
Adaptive Headlights	<ul style="list-style-type: none"> 7% of owners not aware of system System does not require driver input 	<ul style="list-style-type: none"> System considered to improve safety Large percentage prefer system to standard headlight systems More willing to drive at night with system 	<ul style="list-style-type: none"> 5-10% decrease in liability claims Potential 2-5% crash reduction Potential reduction of 2,700 pedestrian-related crashes per year 18% report better visibility 	Moderate to high
Voice Activated Control	<ul style="list-style-type: none"> More difficulty using system than younger drivers Greater distraction and decrements in driving performance compared to younger drivers 	<ul style="list-style-type: none"> System considered favorably Most want the system in next vehicle 	<ul style="list-style-type: none"> Produces less cognitive distraction than manual controls Produces greater distraction than interacting with passengers and engaging in other non-driving activities 	Moderate
Drowsiness/Fatigue Warning	<ul style="list-style-type: none"> Confusion about what warning indicates Most systems still prototypes and not yet tested with older drivers 	<ul style="list-style-type: none"> Agreement that system could lead to increased safety Concerns about system's functional limitations 	<ul style="list-style-type: none"> No clear effect on driver performance in traffic conflict situations No significant effect on the number of safety critical events 	Too early to assess

Blind spot warning (BSW) systems

Given the difficulties that many older drivers have with turning their heads to check the areas around their vehicles, BSW systems could have significant value for older drivers. Studies with older drivers have shown not only that the systems have prevented crashes, but also that their use can promote more frequent mirror checking and increase situational awareness. Some work has found a decreased use of turn signals among older adults using a BSW system, however when the system is combined with a LDW system, turn signal use has been shown to increase for this age group. Some results with older drivers also suggest that this group may place too much trust or be overconfident in the system and that BSW systems could increase distraction. This suggests that training on BSW systems would be useful for older drivers. False alarms during bad weather are also reported by older drivers, indicating the need for better future designs or the ability to turn off the system under conditions in which it performs poorly. Overall, we recommend BSW systems for older drivers and suggest that that be coupled with other advanced collision warning systems.

Parking assist (PA) systems

Given that older drivers report parking and backing up to be difficult and stressful, technologies that help older adults do these tasks more safely and effectively would be welcome for this group. The research shows that backup cameras alone have no significant impact on backing up safety, primarily because older drivers tended not to look at them. Adding enhancements to the backup video display such as obstacle detection warnings or distance-to-obstacle information, however, does seem to help older adults notice obstacles behind the vehicle of which they were previously unaware, park more squarely in parking spaces, and reduce stress. PA systems that provide cross-traffic alerts seem like they would be valuable for older drivers, yet little research had addressed the use of these systems with them. Those studies that have utilized older drivers, have found little change in backing behavior and high levels of false alarms. More research with older adults is needed before cross-traffic alert systems can be recommended for older drivers. Older driver research on PA systems that take over the steering component of parallel parking have clearly shown that these systems provide numerous benefits for older adults, including a reduction in stress and mental workload and improved parking. Thus, we highly recommend semi-autonomous parallel parking assist systems for older adults.

Intersection assistance (IA) systems

Intersections are high-frequency crash locations for older drivers. Technologies that can help older drivers safely negotiate intersections, particularly in making safe turns across on-coming traffic, have the potential to keep older adults driving safely for a longer period of time. Unfortunately, IA systems are not sufficiently developed to recommend them for older drivers at this time. We can see some value to older drivers in providing intersection signage on an in-vehicle display, but such a system has not been tested in a real-world setting. We also see great value in systems that provide gap-acceptance advice for older drivers, but these systems are mainly conceptual at this time and as such have only been

evaluated in simulation. With the advances in connected-vehicle technologies that will undoubtedly come in the future, functional IA systems will be developed and these systems should be tested with older adults.

Merging assistance (MA) systems

While merging onto a motorway is not a significant issue for drivers, data do show that older adults are overrepresented in merging-related crashes. These systems are relatively new, the safety impacts are not yet known, and no research has been conducted that utilized drivers age 65 and older. MA systems that provide advice on merging gaps or warnings about merging conflicts would be moderately valuable for older drivers if they were coupled with other crash avoidance technologies. These systems will also benefit from the development of connected-vehicle technologies and research on future systems should include older drivers.

Navigation assistance (NA) systems

Some older drivers report difficulty in wayfinding and many older adults report being uncomfortable driving in unfamiliar areas. An abundance of evidence suggests that NA systems provide many benefits to older drivers provided that the interfaces are easy-to-use and intuitive. NA systems are frequently used and highly regarded by older adults. We highly recommend NA systems for older drivers.

Congestion warning (CW) systems

Older drivers report concerns about driving in areas of non-recurrent congestion, including work zones and accident zones. The data on older drivers and CW systems are sparse. However, research among other age groups shows that these systems can lead to earlier and smoother deceleration while entering into traffic congestion, which is promising to reduce the chances of rear-end collisions due to changes in traffic flow. One on-road study, found that older drivers reacted just as quickly as younger drivers to upcoming traffic congestion. Some negative effects, however, need to be noted, such as the systems caused distraction and decreased minimum time to collision. These systems were rated as useful and satisfactory in simulator studies, whereas they were not highly regarded in testing on actual roadways in part due to the high false alarm rate. CW systems are another technology that will likely benefit from improvements in connected-vehicle technologies and its functionality still needs to be improved before we can recommend them for older drivers.

Intelligent speed adaptation (ISA) systems

Although speeding is a frequent contributing factor in motor vehicle crashes, it is a relatively uncommon behavior among older adults. This is, perhaps, why so few studies of ISA systems have included older drivers. In general, ISA systems are not positively received by drivers and do not impact speeding behaviors unless they actively slow down vehicles that are speeding. We see little value of ISA systems, in general, for older drivers.

Adaptive cruise control (ACC) systems

A large literature exists for ACC systems and older drivers. This literature shows that older drivers value ACC systems for their comfort and convenience. Older drivers frequently used ACC systems and had lower levels of stress and workload while using the systems. On the negative side, however, ACC system use by older adults can result in reduced situational awareness, late braking for critical events, and overconfidence in the system. These negative effects are thought to arise from older drivers (and drivers of other ages) not fully understanding the situations under which ACC systems do and do not operate, such as automatically stopping the vehicle in the presence of a stopped lead vehicle. These negative effects are not generally seen in tests of ACC during natural driving, but the situations in which the ACC system would fail are rarely encountered in natural driving. Thus, we recommend ACC systems for older drivers, but these systems should come with proper training not only on the operation of the systems but also on the situations for which the ACC systems are not designed to operate.

Automatic crash notification (ACN) systems

Given the higher fatal crash rate and the increased likelihood of severe injury in older adulthood, any technology that can improve the chances of an older adult surviving a crash is recommended. ACN systems have been shown to reduce fatalities in crashes, although this has not been established among older adults. ACN systems operate automatically without any interaction from the driver. We conclude that ACN systems would be highly valuable for older drivers.

Night vision enhancement (NVE) systems

A problem commonly cited by older drivers is an inability to see well at night while driving. The amount of literature on NVE systems and older drivers is modest. The work that has been done, however, shows that many of the benefits (such as increased ability to detect pedestrians) have only been found for younger drivers. Because the safety benefits of NVE systems have not been firmly established for older drivers, we do not recommend these systems. Additional research is needed with older drivers using these systems under normal driving conditions. This work should address not only the safety benefits, but also the impact on increased mobility while using a NVE system.

Adaptive headlight (AH) systems

Studies have estimated that AH systems can reduce nighttime crashes, particularly those involving a pedestrian. Although these studies do not provide estimates for the older driver population, to the extent that older people are driving at night, these benefits are likely to extend to this age group. Data with older drivers show that AH systems can improve the detection of objects and reduce the disability glare from oncoming traffic. There is also evidence that older adults may drive faster at night when using an AH system, which may or may not decrease safety. Of older drivers who have used the systems, about 1 in 5 report better nighttime visibility, a large majority prefer them to standard headlight systems, and most believe that they improve safety. We conclude that AH systems could provide moderate-to-high value for older drivers.

Voice activated control (VAC) systems

As the number and complexity of advanced in-vehicle systems continue to grow, there will be a need to make interfacing with these systems as intuitive and simple as possible. VAC systems are a promising method for making interactions with in-vehicle and nomadic technologies easier and safer. One needs to keep in mind that simply engaging with several technologies while driving can increase workload whether it is through a manual or voice control system. The data show that VAC systems produce less cognitive distraction than manual controls, and that distraction is greater than interacting with passengers and engaging in many other non-driving activities. However, advanced technologies are already present in vehicles and the future vehicles will likely contain many more. Older drivers will be using these technologies and we recommend VAC systems as an optional way to interact with the technologies.

Drowsiness/Fatigue warning (DW) systems

The evidence for the effectiveness of DW systems is sparse. Although there are a number of approaches being taken to develop a system that can reliably, accurately, and in a timely fashion detect drowsiness and intervene with the driver, none of these approaches yet meet all of these criteria. These systems continue to be refined and tested, but are not to the point where they can be recommended for older drivers. As these systems are being developed, they should be tested with older drivers, particularly among older drivers who may experience drowsiness related to medication use rather than from a lack of sleep. Further, the currently available "driver state warning" systems that operate based on detection of the vehicle drifting in the lane are in large part misunderstood by drivers and found to be annoying. These systems are also not recommended for older drivers.

Conclusion

As described by Yang and Coughlin (2014), "Older drivers represent an innovation paradox when purchasing vehicles." (pg. 335). Many new advanced in-vehicle technologies first become available in relatively expensive vehicles that are more likely to be bought by older adults who have the resources to purchase them. Older drivers, therefore, are and will continue to be a critical test market for new automotive technologies. The successful design, implementation, and marketing of these technologies will require special consideration of the unique needs, attitudes, and capabilities of older drivers. Although not extensively discussed in this review, people with hearing deficits, visual deficits, or cognitive impairment may have difficulty hearing, seeing, and responding to warnings and thus may not be able to experience the full benefits of these technologies.

Training and Education

A number of studies suggest that older drivers have more difficulties and take longer to learn how to use advanced technologies (see e.g., AAAFTS, 2008; Caird, 2004; Kostyniuk, Streff, & Eby, 1997). Other research has found that older adults have concerns about how to use some technologies, lack full understanding of the function and capabilities of some systems, and misunderstand how some systems improve safety (Dickie & Boyle, 2009; Owsley, McGwin, & Seder, 2011; Piccini et al., 2015; Shaw et al., 2010). Advanced in-vehicle technologies that are poorly understood or misused could lead to a range of negative outcomes from creating a barrier for acceptance to increasing the risk of a crash.

How do older drivers learn how to use new in-vehicle technologies? There is surprisingly little information available to answer this question. Studies by the Insurance Institute for Highway Safety involving interviews with owners of vehicles equipped with various advanced in-vehicle technologies have found that a small percentage of owners (1-30 percent depending on the technology) were not even aware that their vehicle had the technology, suggesting that at least some owners never received any instruction on how to use it (Braitman et al., 2010; Eichelberger & McCartt, 2014a). A questionnaire study by the AAA Foundation for Traffic Safety (2008) with older adults who owned vehicles equipped with ACC, backing aid, rear-view camera, and navigation assistance systems addressed how they learned to use the technologies in their vehicle. The study found three predominant modes for learning about these systems: instructions from the dealership (31-62 percent); the vehicle owner's manual (40-75 percent); and trial-and-error while on the road (41-50 percent). A surprising 2-20 percent reported that they had not yet learned how to use the system. One goal of the AAAFTS sponsored LongROAD project is to investigate how older drivers learn to use advanced technologies as well as how they are used and thought about among a diverse sample of 3,000 older drivers. These results should provide fruitful insights into the training and education needs of older adults.

There seems to be a clear need and opportunity to improve the way manufacturers train older adults about new in-vehicle technologies. As many readers will attest: the experience of purchasing a vehicle from a dealership leaves too little time for the dealer to acquaint the new owner with vehicle features and to also provide training on the new advanced in-vehicle technologies; vehicle owner's manuals can be complicated and difficult to understand; and learning a new technology by trial and error can lead to a

misunderstanding of how the systems operate and can compromise safety. As suggested by some researchers (Coughlin, 2009; Eby & Molnar, 2014; Reimer, 2014), vehicle and technology manufacturers may have to come up with new ways of training drivers to use new in-vehicle systems.

Research Needs

This synthesis has reviewed a large body of research related to older drivers and advanced in-vehicle technologies; yet only a handful of the studies have included samples with the age groups considered by many researchers in the field of aging and driving to be "older drivers." Based on changes in fatal crash rates (see Figure 1), driving patterns, and general health status, contemporary studies commonly define an older driver as being age 70 or 75 and older (see e.g., Eby et al., 2011; Cuenen et al., 2015; Marshall et al., 2013; Molnar et al., 2013; Staplin, Gish, & Sifrit, 2014). Population projections also show that many countries will experience a significant increase in the oldest-old; that is, people age 80 and older (NIA, 2011). The oldest-old are often very different in their driving needs and patterns in ways that might impact use of technologies (Eby et al., 2011; Langford et al., 2013). Research on the use, safety, and acceptance of advanced in-vehicle technologies should redefine the age for an "older driver" and start to consider how these oldest age groups are impacted by new technologies. While the LongROAD project will be enrolling participants starting between age 65 and 79, as the project progresses most participants will be at least age 70 and many will be much older by the study completion.

Similarly, studies have shown that, in many cases, older adults use in-vehicle technologies differently than younger drivers. For example, older adults report using navigation assistance (NA) systems with a passenger "co-navigator," who is usually a spouse (Kostyniuk, Streff, & Eby, 1997; Vrkljan & Polgar, 2007). The co-navigator operates the NA system while the driver executes the maneuvers, seemingly incorporating the NA system into their normal wayfinding driver/co-navigator method. If the in-vehicle technology does not allow input while the vehicle is in operation, as is the case for many NA systems, then the driver may not use the system because it does not fit with his or her well-learned wayfinding method. This example illustrates that for new technologies to be safe and acceptable for older adults, it cannot be assumed that older adults, especially the oldest-old will use these technologies in the same way as younger drivers. Also, as discussed in a recent report that evaluated the safety benefits of several automotive technologies (Mehler, et al., 2014b), many technologies have great potential to improve safety but there are limited data on the safety benefits of these technologies that have been determined objectively in real-world driving conditions. The actual benefits may not match the projected benefits. These data are even more limited when considering just the older age group. Thus, as suggested by many researchers, more knowledge is needed about how advanced in-vehicle technology are used in real-world settings where natural driving behaviors can occur (Kostyniuk, Streff, & Eby, 1997; Mehler, et al., 2014b; Paris et al., 2014).

Extending Safe Driving among Older Drivers

We began this paper by posing the question: Can advanced in-vehicle technologies help extend the period over which an older adult can drive safely? We answer this question with an optimistic "yes." Some of technologies reviewed here have been shown to help older drivers avoid crashes, improve the ease and comfort of driving, and travel to places and at times that they might normally avoid. Other technologies show promise for providing benefits to older drivers and the development of these technologies continues. Although this report generally reviewed the technologies in isolation, the reality is that these technologies are being designed to work together as integrated in-vehicle systems (see e.g., Sayer et al., 2010). Designers of integrated systems strive to not only make using all of the technologies easier, but they also attempt to overcome the weaknesses of one system with the strengths of another.

The cutting edge of automotive safety and driver assistance technologies is moving beyond in-vehicle systems. Future technologies will involve vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) sharing of information that will enhance existing in-vehicle systems, such as congestion warning, intersection assistance, and merging assistance systems. Development of these technologies is also paving the way to autonomous vehicles (also called "driverless cars" and "self-driving cars"). The potential benefits of autonomous vehicles as a means for reducing traffic crashes and maintaining mobility among older adults has been mentioned regularly in the media. In an article in the New York Times, Chris Urmson, Director of Self-Driving Cars at Google, cited older drivers and blind people as the groups who would receive the greatest benefits from autonomous vehicles (Kessler, 2015). Several other media stories have also cited the particular benefits of autonomous vehicles for the older adult demographic (see e.g., Berk, 2014; Antoville, 2014; McLaughlin, 2014; O'Connor, 2013). We consider the older adult an ideal age group for identifying challenges in the development of future in-vehicle, V2V, V2I, and autonomous vehicle technologies. The solutions to the challenges that older adults present for these advanced safety and driver assistance technologies will likely apply to other age groups.

References

- AAAFTS (2008). *Use of Advanced In-Vehicle Technology by Younger and Older Early Adopters*. Washington, DC: AAA Foundation for Traffic Safety.
- Abdel-Aty, M.A. & Radwan, A.E. (2000). Modeling traffic accident occurrence and involvement. *Accident Analysis & Prevention*, **32**, 633-642.
- Adell, E., Vårhelyi, A., & Fontana, M.D. (2011). The effects of a driver assistance system for safe speed and safe distance—A real-life field study. *Transportation Research Part C*, **19**, 145-155.
- Alicandri, E. (1998). *An Investigation of Older Driver Freeway Needs and Capabilities*. Report No. FHWA-RD-98-162. Washington, DC: Federal Highway Administration.
- Alvarez, F.J. & Fierro, I. (2008). Older drivers, medical conditions, medical impairment and crash risk. *Accident Analysis & Prevention*, **40**, 55-60.
- Amano, K. & Tsugawa, S. (2010). Merging assistance at a non-signalized intersection with vehicle-to-vehicle communications. In *Proceedings of the 17th ITS World Congress*. Washington, DC: ITS America.
- Ando, R., Ono, T., Obayashi, F., Mimura, Y., Kozuka, K., & Ozawa, S. (2014). Effect Analysis of Intelligent Speed Adaptation (ISA) in Advisory Mode on Community Roads. *Procedia Computer Science*, **32**, 277-284.
- Anshel, M.H. (1978). Effect of aging on acquisition and short-term retention of a motor skill. *Perceptual Motor Skills*, **47**, 993-994.
- Anstey, K.J., Wood, J., Lord, S., & Walker, J.G. (2005). Cognitive, sensory and physical factors enabling driving safety in older adults. *Clinical Psychology Review*, **25**, 45-65.
- Antoville, A. (2014). Self-driving cares: A solution for aging drivers. *Compassionate Aging*. URL: <http://www.compassionateaging.org/self-driving-cars-a-solution-for-aging-drivers/>.
- Attebo, K., Mitchell, P., & Smith, W. (1996). Visual acuity and the causes of visual loss in Australia: The Blue Mountain Eye Study. *Ophthalmology*, **103**, 357-364.
- Baldock, M.R.J., Mathias, J.L., McLean, A.J., & Berndt, A. (2006). Self-regulation of driving and its relationship to driving ability among older adults. *Accident Analysis & Prevention*, **38**, 1038-1045.
- Baldwin, C. (2002). Designing in-vehicle technologies for older drivers: Sensory-cognitive interaction theory. *Theoretical Issues in Ergonomic Science*, **3(4)**, 307-329.

- Ball, K.K., Beard, B.L., Roenker, D.L., Miller, R.L., & Griggs, D.S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America*, **5**, 2210-2219.
- Ball, K. & Sekuler, R. (1986). Improving visual perception in older observers. *Journal of Gerontology*, **41**, 176-182.
- Balkin, T.J., Horrey, W.J., Graeber, R.C., Czeisler, C.A., & Dinges, D.F. (2011) The challenges and opportunities of technological approaches to fatigue management. *Accident Analysis & Prevention*, **43**, 565-572.
- Band, D. & Perel, M. (2007). Senior mobility series: Article 8 new vehicle technologies may help older drivers. *Public Roads*, **71**, 1-14.
- Barón, A & Green, P. (2006). *Safety and Usability of Speech Interfaces for In-Vehicle Tasks while Driving: A Brief Literature Review*. Report No. UMTRI-2006-5. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Bato, J.A. & Boyle, L.N. (2011). Adaptive cruise control user differences in urban and rural environments. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, **55(1)**, 1943-1947.
- Becic, E., Manser, M., Creaser, J.L., & Donath, M. (2012). Intersection crossing assist system: Transition from a road-side to an in-vehicle system. *Transportation Research Part F*, **15**, 544-555.
- Becic, E., Manser, M., Drucker, C., & Donath, M. (2013). Aging and the impact of distraction on an intersection crossing assist system. *Accident Analysis & Prevention*, **50**, 968-974.
- Bell, M.D., Wolf, E., & Bernholz, C.D. (1972). Depth perception as a function of age. *Aging & Human Development*, **3**, 77-81.
- Berk, B. (2014). Self-driving cars could keep seniors in the driver's seat. *The Dallas Morning News*. URL: <http://www.dallasnews.com/opinion/latest-columns/20140415-self-driving-cars-could-keep-seniors-in-the-drivers-seat.ece>.
- Berryman, M.E. (2004). Automatic crash notification and 9-1-1: A success story. In *Proceedings 2004 ESRI Users Conference*. Redlands, CA: ESRI International.
- Birren, J.E. & Shock, N.W. (1950). Age changes in rate and level of dark adaptation. *Journal of Applied Psychology*, **26**, 407-411.
- Blanco, M., Bocanegra, J.L., Morgan, J.F., Fitch, G.M., Medina, A., Olson, R.L., Hanowski, R.J., Daily, B., & Zimmerman, R.P. (2009). *Assessment of a Drowsy Driver Warning System for Heavy-Vehicle Drivers: Final Report*. Report No. DOT HS 811 117. Washington, DC: National Highway Traffic Safety Administration.

- Blaschke, C., Breyer, F., Färber, Freyer, J., & Limbacher, R. (2009). Driver distraction based lane-keeping assistance. *Transportation Research Part F*, **12**, 288-299.
- Blower, D. (2014). *Assessment of the Effectiveness of Advanced Collision Avoidance Technologies*. Report No. UMTRI-2014-3. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Bogler, B., Cody, D., Geyer, J., Horne, J.H., Misener, J.A., Nowakowski, C., Rodier, C.J., Ragland, D., Shaheen, S.A., Caguimbaga, J., Daniels, B., & Hamel, K. (2005). *Investigation of Elderly Driver Safety and Comfort: In-Vehicle Intersection "Gap-Acceptance Advisor" and Identifying Older Driver Needs*. Report No. UCB-ITS-PRR-2005-36. Berkeley, CA: California Path Program, Institute of Transportation Studies, University of California, Berkeley.
- Bowman, D., Hanowski, R.J., Alden, A., Gupta, S., Wiegand, D., Baker, S., Stanley, L.M., & Wierwille, W. (2012). *Development and Assessment of a Driver Drowsiness Monitoring System*. Report No. FMCSA-RRR-12-008. Washington, DC: Federal Motor Carrier Safety Administration.
- Braitman, K.A., McCartt, A.T., Zuby, D.S., & Singer, J. (2010). Volvo and Infiniti drivers' experience with select crash avoidance technologies. *Traffic Injury Prevention*, **11**, 270-278.
- Brookhuis, K.A., Van Driel, C.J.G., Hof, T., van Arem, B., & Hoedemaeker, M. (2008). Driving with a congestion assistant: Mental workload and acceptance. *Applied Ergonomics*, **40**, 1019-1025.
- Brown, T., He, Y., Roe, C., & Schnell, T. (2010). Is more better?—Night vision enhancement system's pedestrian warning system modes and older drivers. *Annals of the Association for the Advancement of Automotive Medicine*, **54**, 343-350.
- Bryden, K.J., Charlton, J.L., Oxley, J.A., & Lowndes, G.J. (2013). Self-reported wayfinding ability of older adults. *Accident Analysis & Prevention*, **59**, 277-282.
- Buehler, R., & Nobis, C. (2010). Travel behavior in aging societies: Comparison of Germany and the United States. *Transportation Research Record*, **2182**, 62-70.
- Burg, A. (1966). Visual acuity as measured by dynamic and static tests. *Journal of Applied Psychology*, **50**, 460-466.
- Caird, J.K. (2004). In-vehicle intelligent transportation systems: Safety and mobility of older drivers. In *Transportation in an Aging Society: A Decade of Experience*. Washington, DC: Transportation Research Board.
- Caird, J.K., Chisholm, S.L., Lockhart, J., Vacha, N., Edwards, C.J., Creaser, J.I., & Hatch, K. (2006). *In-Vehicle intelligent Transportation System (ITS) Countermeasures to Improve Older Driver Intersection Performance*. Report No. TP 14610E. Montreal, Canada: Transportation Development Centre, Transport Canada.

- Carsten, O.M.J. & Tate, F.N. (2005). Intelligent speed adaptation: accident savings and cost-benefit analysis. *Accident Analysis & Prevention*, **37**, 407-416.
- Champion, H.R., Augenstein, J.S., Blatt, A.J., Cushing, B. Digges, K.H., Hunt, R.C., Lombardo, L.V., & Siegel, J.H. (2003). Reducing highway deaths and disabilities with automatic wireless transmission of serious injury probability ratings from vehicles in crashes to EMS. In *Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles*. Washington, DC: US Department of Transportation.
- Chan, M. & Rose, G. (2002). *Navigation and Travel Behaviour: Findings from Focus Group Results*. Report No. ITS-WP-01-18. Sydney, New South Wales: Institute of Transport and Logistics Studies, Faculty of Economics and Business.
- Charlton, J., Koppel, S., O'Hare, M., Andrea, D., Smith, G., Khodr, B., Langford, J., Odell, M., & Fildes, B. (2004). *Influence of Chronic Illness on Crash Involvement of Motor Vehicle Drivers*. Report No. 213. Victoria, Australia: Monash University Accident Research Centre.
- Charlton, J.L., Oxley, J., Fildes, B., Oxley, P., Newstead, S., Koppel, S., & O'Hare, M. (2006). Characteristics of older drivers who adopt self-regulatory driving behaviours. *Transportation Research Part F*, **9**, 363-373.
- Chiang, D.P., Brooks, A.M., & Weir, D.H. (2005). *Comparison of Visual-Manual and Voice Interaction with Contemporary Navigation System HMIs*. Report No. 2005-01-0433. Warrendale, PA: SAE International.
- Chihuri, S., Mielenz, T.J., DiMaggio, C.J., Betz, M.E., DiGuseppi, C., Jones, V.C., & Li, G. (2015). *Driving Cessation and Health Outcomes in Older Adults*. Washington, DC: AAA Foundation for Traffic Safety.
- Chorlton, K., Hess, S., Jamson, S., & Wardman, M. (2012). Deal or no deal: Can incentives encourage widespread adoption of intelligent speed adaptation devices? *Accident Analysis & Prevention*, **48**, 73-82.
- Chouinard, A. & Lécuyer, J-F. (2011). A study of the effectiveness of Electronic Stability Control in Canada. *Accident Analysis & Prevention*, **43**, 451-460.
- Chun, J., Lee, I., Park, G., Seo, J., Choi, S. & Han, S.H. (2013). Efficacy of haptic blind spot warnings applied through a steering wheel or seatbelt. *Transportation Research Part F*, **21**, 213-241.
- Cicchino, J.B., Eichelberger, A.H. & McCartt, A.T. (2015). Buick Lucerne drivers' experiences with rear parking sensors. *Traffic Injury Prevention*, **16**, 196-201.
- Cicchino, J.B. & McCartt, A.T. (2014). *Experiences of Dodge and Jeep Owners with Collision Avoidance and Related Technologies*. Arlington, VA: Insurance Institute for Highway Safety.

- Clark, D.D., Forsyth, R., & Wright, R. (1999). Junction road accidents during cross-flow turns: A sequence analysis of police case files. *Accident Analysis & Prevention*, **31**, 31-43.
- Clark, D.E. & Cushing, B.M. (2002). Predicted effect of automatic crash notification on traffic mortality. *Accident Analysis & Prevention*, **34**, 507-513.
- Comte, S.L. (2000). New systems: New behaviour? *Transportation Research Part F*, **3**, 95-111.
- Cooner, S.A. & Wiles, P.B. (2006). *Review of Current Practices for Advanced Warning of Slow/Stopped Traffic on Freeways*. Arlington, TX: Texas A&M Transportation Institute.
- Cooper, P. (1990). Differences in accident characteristics among elderly drivers and between elderly and middle-aged drivers. *Accident Analysis & Prevention*, **5**, 499-508.
- Cotté, N., Meyer, J., & Coughlin, J.F. (2001). Older and younger drivers' reliance on collision warning systems. In *Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.
- Coughlin, J.F. (2009). Longevity, lifestyle, and anticipating the new demands of aging on the transportation system. *Public Works Management & Policy*, **13**, 301-311.
- Creaser, J., Rakauskas, M., Ward, N., & Laberge, J. (2007). *A Simulator-Based Evaluation of Smart Infrastructure Concepts for Intersection Decision Support for Rural Thru-STOP Intersections*. Report No. MN/RC-2007-31. St. Paul, MN: Minnesota Department of Transportation.
- Cuenen, A., Jongen, E.M.M., Brijs, T., Lutin, M., van Vlierden, K., & Wets, G. (2015). Does attention capacity moderate the effect of driver distraction in older drivers? *Accident Analysis & Prevention*, **77**, 12-20.
- Cummings, M.L., Kilgore, R.M., Wang, E., Tijerina, L., & Kochhar, D.S. (2007). Effects of single versus multiple warnings on Driver Performance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, **49**, 1097-1106.
- Daigneault, G., Joly, P., & Frigon, J-Y. (2002). Executive functions in the evaluation of accident risk of older drivers. *Journal of Clinical and Experimental Neuropsychology*, **24(2)**, 221-238.
- Dang, J.N. (2007). *Statistical Analysis of the Effectiveness of Electronic Stability Control (ESC) Systems – Final Report*. Report No. DOT HS 810 794. Washington, DC: National Highway Traffic Safety Administration.
- Davidse, R.J., Hagenzieker, M.P., van Wolffelaar, P.C., & Brouwer, W.H. (2009). Effects of in-car support on mental workload and driving performance of older drivers.

Human Factors: The Journal of the Human Factors and Ergonomics Society, **51(4)**, 463-476.

- de Winter, J.C.F., Happee, R., Martens, M.H., & Stanton, N.A. (2014). Effects of adaptive cruise control and highly automated driving on workload and situation awareness: A review of the empirical evidence. *Transportation Research Part F: Traffic Psychology and Behaviour*, **27**, 196-217.
- Deroo, M., Hoc, J-M., & Mars, F. (2012). Influence of risk expectation on haptically cued corrective manoeuvres during near lane departure. *Ergonomics*, **4**, 465-475.
- Dickerson, A.E., Molnar, L.J., Eby, D.W., Adler, G., Bédard, M., Berg-Weger, M., Classen, S., Foley, D., Horowitz, A., Kerschner, H., Page, O., Silverstein, N.M., Staplin, L., & Trujillo, L. (2007). Transportation and aging: A research agenda for advancing safe mobility. *The Gerontologist*, **47**, 578 - 590.
- Dickie, D.A. & Boyle, L.N. (2009). Drivers' understanding of adaptive cruise control limitations. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, **53**, 1806-1810.
- Dingus, T., Hulse, M.C., Mollnehauer, M.A., Fleischman, R.N., McGehee, D.V., & Manakkal, N. (1997). Effects of age, system experience, and navigation technique on driving with an advanced traveler information system. *Human Factors*, **39**, 177–179.
- Dobbs, B.M. (2005). *Medical Conditions and Driving: A Review of the Scientific Literature (1960-2000)*. (Report No. DOT HSW 809 690). Washington, DC: US Department of Transportation.
- Doecke, S.D., & Woolley, J.E. (2011). *Cost Benefit Analysis of Intelligent Speed Adaptation*. Report No. CASR093. South Australia, Australia: University of Adelaide, Centre for Automotive Safety Research.
- Dotzauer, M., Caljouw, S.R., de Waard, D., & Brouwer, W.H. (2013). Intersection assistance: A safe solution for older drivers? *Accident Analysis & Prevention*, **59**, 522-528.
- Dotzauer, M., de Waard, D., Caljouw, S.R., Pöhler, G., & Brouwer, W.H. (2014). Behavioral adaptation of young and older drivers to an intersection crossing advisory system. *Accident Analysis & Prevention*, **74**, 24-32.
- Douissembekov, E., Gabaude, C., Rogé, J., Navarro, J., & Michael, G.A. (2014). Parking and manoeuvring among older drivers: A survey investigating special needs and difficulties. *Transportation Research Part F: Traffic Psychology and Behaviour*, **26**, 238-245.
- Druid, A. (2002). *Vision Enhance System-Does Display Position Matter?* Master's Thesis. Vargarda, Sweden: Linkoping University.

- Eby, D.W. & Kostyniuk, L.P. (1998). Maintaining older driver mobility and well-being with traveler information systems. *Transportation Quarterly*, 52, 45-53.
- Eby, D.W. & Kostyniuk, L.P. (1999). An on-the-road comparison of in-vehicle navigation assistance systems. *Human Factors*, 41, 295-311.
- Eby, D.W. & Molnar, L.J. (1999). *Guidelines for Developing Information Systems for the Driving Tourist*. Report No. ITS-RCE-939430. Ann Arbor, MI: The University of Michigan Intelligent Transportation System Research Center of Excellence.
- Eby, D.W. & Molnar, L.J. (2014). Has the time come for an older driver vehicle? *Journal of Ergonomics*. S3: 002. doi:10.4172/2165-7556.S3-002.
- Eby, D.W., Molnar, L.J., & Kartje, P.S. (2009). *Maintaining Safe Mobility in an Aging Society*. New York, NY: CRC Press. ISBN: 9781420064537.
- Eby, D.W., Molnar, L.J., Kostyniuk, L.P., St. Louis, R.M., & Zanier, N. (2011). *Recommendations for Meeting the Needs of Michigan's Aging Population*. Report No. RC-1562. Lansing, MI: Michigan Department of Transportation.
- Eby, D.W., Trombley, D., Molnar, L.J., & Shope, J.T. (1998). *The Assessment of Older Driver's Capabilities: A Review of the Literature*. Report No. UMTRI-98-24. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Eby, D.W., Silverstein, N.M., Molnar, L.J., LeBlanc, D., & Adler, G. (2012). Driving behaviors in early stage dementia: A study using in-vehicle technology. *Accident Analysis & Prevention*, 49, 324-331.
- Edwards, C., Morris, N., & Manser, M. (2013). *A Pilot Study on Mitigating Run-Off-Road Crashes*. Report No. CTS 13-23. Minneapolis, MN: Intelligent Transportation Systems Institute, Center for Transportation Studies.
- Edwards, J., Lunsman, M., Perkins, M., Rebok, G., & Roth, D. (2009). Driving cessation and health trajectories in older adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, 64A(12), 1290-1295.
- Eichelberger, A. H. & McCartt, A.T. (2014a). *Toyota Drivers' Experiences with Dynamic Radar, Cruise Control, the Pre-Collision System, and Lane-Keeping Assist*. Arlington, VA: Insurance Institute for Highway Safety.
- Eichelberger, A.H. & McCartt, A.T. (2014b). Volvo drivers' experiences with advanced crash avoidance and related technologies. *Traffic Injury Prevention*, 15(2), 187-195.
- Emmerson, C., Guo, W., Blythe, P., Namdeo, A. & Edwards, S. (2013). Fork in the road: In-vehicle navigation systems and older drivers. *Transportation Research Part F*, 21, 173-180.

- Eriksson, L. & Bjørnskau, T. (2012). Acceptability of traffic safety measures with personal privacy implications. *Transportation Research Part F*, **15**, 333-347.
- Ervin, R.D., Sayer, J., LeBlanc, D., Bogard, S., Mefford, M., Hagan, M., Bareket, Z., & Winkler, C. (2005). *Automotive Collision Avoidance System Field Operational Test Report: Methodology and Results*. Report No. DOT HS 809 900. Washington, DC: US Department of Transportation.
- Fancher, P., Ervin, R., Sayer, J., Hagan, M., Bogard, S., Bareket, Z., Mefford, M., & Haugen, J. (1998). *Intelligent Cruise Control Field Operational Test (Final Report)*. Report No. UMTRI-98-17. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Ferguson, S.A. (2007). The effectiveness of electronic stability control in reducing real-world crashes: A literature review. *Traffic Injury Prevention*, **8**, 329-338.
- Fillit, H. & Butler, R.N. (2009). The frailty identity crisis. *Journal of the American Geriatrics Society*, **57**, 348-352.
- Fitch, G.M., Bowman, D.S., & Llaneras, R.E. (2014). Distracted driver performance to multiple alerts in a multiple-conflict scenario. *Human Factors*, **56(8)**, 1497-1505.
- French, D.J., West, R.J., Elander, J., & Wilding, J.M. (1993). Decision-making style, driving style, and self-reported involvement in road traffic accidents. *Ergonomics*, **36**, 627-644.
- Garvill, J., Marell, A., & Westin, K. (2003). Factors influencing drivers' decision to install an electronic speed checker in the car. *Transportation Research Part F*, **6**, 37-43.
- Gish, K.W., Shoulson, M., & Perel, M. (2002). Driver Behavior and Performance Using an Infrared Night Vision Enhancement System. Paper 02-2355. Presentation at the 81st Annual Meeting of the Transportation Research Board, Washington, DC.
- Gish, K.W., Staplin, L., & Perel, M. (1999). Human factors issues related to use of vision enhancement systems. *Transportation Research Record*, **1694**, 1-9.
- Golz, M., Sommer, D., Trutschel, U., Sirois, B., & Edwards, D. (2010). Evaluation of fatigue monitoring technologies. *Somnologie*, **14**, 187-199.
- Guo, F., Wotring, B.M., & Antin, J. F. (2010). *Evaluation of Lane Change Collision Avoidance Systems Using the National Advanced Driving Simulator*. Report No. DOT HS 811 332. Washington, DC: National Highway Traffic Safety Administration.
- Hakamies-Blomqvist, L. (2004). Safety of older persons in traffic. In *Transportation in an Aging Society: A Decade of Experience*. Washington, DC: Transportation Research Board.

- Hakamies-Blomqvist, L., Raitanen, T., & O'Neill, D. (2002). Driver ageing does not cause higher accident rates per km. *Transportation Research Part F*, **5**, 271-274.
- Hankey, J.M., Kiefer, R.J., & Gibbons, R.B. (2005). *Quantifying the Pedestrian Detection Benefits of the General Motors Night Vision System*. Report No 205-01-0443. Warrendale, PA: SAE International.
- Hatakenaka, H., Kanoshima, H., ya, T., Nishii, S., Mizutani, H., & Nagano, K. (2008). Development and verification of effectiveness of an AHS safe merging support service. In *Proceedings of the 15th World Congress on Intelligent Transport Systems and ITS America's 2008 Annual Meeting*. Washington, DC: ITS America.
- Hayat, M.T., Park, H., & Smith, B.L. (2014). Connected vehicle enabled freeway merge assistance system—Field Test: Preliminary results of driver compliance to advisory. In *Intelligent Vehicles Symposium Proceedings—2014 IEEE*. New York, NY: IEEE.
- He, J., Chaparro, A., Nguyen, B., Burge, R.J., Chandall, J., Chaparro, B., & Cao, S. (2014). Texting while driving: Is speech-based text entry less risky than handheld text entry? *Accident Analysis & Prevention*, **72**, 287-295.
- Heaslip, K., Collura, J., & Knodler Jr., M.A. (2009). Evaluation of work-zone design features to aid older drivers. *TRB 88th Annual Meeting Compendium of Papers DVD*. Report No. 09-2131. Washington, DC: Transportation Research Board.
- Heppenstall, C.P., Wilkinson, T.J., Hanger, H.C., & Keeling, S. (2009). Frailty: Dominos or deliberation? *The New Zealand Medical Journal*, **122(1299)**, 42-52.
- Heron, A. & Chown, S.M. (1967). *Age and Function*. London, UK: Churchill.
- Herriotts, P. (2005). Identification of vehicle design requirements for older drivers. *Applied Ergonomics*, **36**, 255-262.
- Hoedemaeker, M. & Brookhuis, K.A. (1998). Behavioural adaptation to driving with an adaptive cruise control (ACC). *Transportation Research Part F*, **1**, 95-106.
- Hofstetter, H.W. & Bertsch, J.D. (1976). Does stereopsis change with age? *American Journal of Ophthalmology & Physiological Optics*, **53**, 664-667.
- Horberrry, T., Hartley, L., Kruger, G.P., & Mabbott, N. (2001). Fatigue detection technologies for drivers: A review of existing operator-centered systems. In *Proceedings People in Control: An International Conference on Human Interfaces in Control Rooms, Cockpits, and Command Centers*. Washington, DC: IEEE
- Hunt, R.C. (2002). Emerging communication technologies in emergency medical services. *Prehospital Emergency Care*, **6(1)**, 131-136.
- Hurwitz, D.S., Pradhan, A., Fischer, D.L., Knodler, M.A., Muttart, J.W., Menon, R. & Meissner, U. (2010). Backing collisions: A study of drivers' eye and backing

- behaviour using combined rear-view camera and sensor systems. *Injury Prevention*, **16**, 79-84.
- Insurance Institute for Highway Safety (2012). They're working: Insurance claims data show which technologies are preventing crashes. *Status Report*, **47(5)**, 1-7.
- Insurance Institute for Highway Safety (2013). *Older Drivers: Older People 2013*. URL: <http://www.iihs.org/iihs/topics/t/older-drivers/fatalityfacts/older-people>. Accessed: February, 2015. Arlington, VA: Insurance Institute for Highway Safety.
- Insurance Institute for Highway Safety (2014). Fit for the road: Older drivers' crash rates continue to drop. *Status Report*, **49(1)**, 2-5.
- Itoh, K., Miki, Y., Yoshitsugu, N., Kubo, N., & Mashimo, S. (2004). *Evaluation of a Voice-Activated System using a Driving Simulator*. Report No. 2004-01-0232. Warrendale, PA, SAE International.
- Jamson, S. (2006). Would those who need ISA, use it? Investigating the relationship between drivers' speed choice and their use of a voluntary ISA system. *Transportation Research Part F: Traffic Psychology and Behaviour*, **9(3)**, 195-206.
- Jamson, S., Chorlton, K., & Carsten, O. (2012). Could Intelligent Speed Adaptation make overtaking unsafe? *Accident Analysis & Prevention*, **48**, 29-36.
- Jani, S.N. (1966). The age factor in stereopsis screening. *American Journal of Ophthalmology*, **43**, 653-657.
- Janke, M.K. (1994). *Age-Related Disabilities that May Impair Driving and their Assessment: Literature Review*. Report No. RSS-94-156. Sacramento, CA: California Department of Motor Vehicles.
- Jenness, J.W., Lattanzio, R.J., O'Toole, M., Taylor, N., & Pax, C. (2002). Effects of manual versus voice-activated dialing during simulated driving. *Perceptual and Motor Skills*, **94**, 363-379.
- Jenssen, G.D., Bjørkli, C.A., Sakshaug, K., & Moen, T. (2007). Behavioural adaptation to adaptive front lighting systems (AFS): A six day driving simulator study. *Proceedings World Congress on Intelligent Transport Systems*, **7**, 5218-5237.
- Jeong, E., Oh, C., & Lee, J. (2014). Evaluation of safety benefits of automatic crash information notification systems on freeways. *International Journal of Automotive Technology*, **15**, 495-503.
- Jermakian, J.S. (2011). Crash avoidance potential of four vehicle technologies. *Accident Analysis & Prevention*, **43**, 732-740.

- Kanianthra, J., Carter, A., & Preziotti, G. (2000). *Field Operational Test Results of an Automated Collision Notification System*. Report No. 2000-01-C041. Warrendale, PA: SAE International.
- Kawabata, Y., Endo, T., Makno, Y., Satonaka, H., Tanaka, Y., & Katoh, M. (2008). Improvement of reverse parking assist with automatic steering. *In Proceedings of the 15th World Congress on Intelligent Transport Systems and ITS America Annual Meeting 2008*. Washington, DC: ITS America.
- Kelso, J.A.S. (1982). *Human Motor Behavior: An Introduction*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Kent, R. (2010). The biomechanics of aging. *NTSB Forum on Safety, Mobility, and Aging Drivers*. Washington, DC: Transportation Research Board.
- Kent, R., Trowbridge, M., Lopez-Valdes, F.J., Ordoyo, R.H., & Segui-Gomez, M. (2009). How many people are injured and killed as a result of aging? Frailty, fragility, and the elderly risk-exposure tradeoff assessed via a risk saturation model. *Annals of Advances in Automotive Medicine*, **53**, 41-50.
- Kessler, A. M. (2015). In Detroit, Google makes a case for driverless cars. *The New York Times*. URL: <http://www.nytimes.com/2015/01/15/business/in-detroit-google-makes-a-case-for-driverless-cars.html? r=0>.
- Kessler, C., Etemad, A., Alessendretti, G., Heinig, K., Selpi, Brouwer, R., Cserpinszky, A., Hagleitner, W., & Benmimoun, M. (2012). *European Large-Scale Field Operational Tests on In-Vehicle Systems: Deliverable D11.3*. Aachen, Germany: euroFOT Consortium.
- Kiefer, R.J. & Hankey, J.M. (2008). Lane change behavior with a side blind zone alert. *Accident Analysis & Prevention*, **40**, 683-690.
- Koppel, S., Bohensky, M., Langford, J., & Taranto, D. (2011). Older drivers, crashes and injuries. *Traffic Injury Prevention*, **12(5)**, 459-467.
- Kostyniuk, L.P., Eby, D.W., Christoff, C., & Hopp, M.L. (1997). *An Evaluation of Driver Response to the TetraStar Navigation Assistance System by Age and Sex*. Report No. UMTRI-97-33. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Kostyniuk, L.P., Streff, F.M., & Eby, D.W. (1997). *The Older Driver and Navigation Assistance Technologies*. Report No. UMTRI-97-47. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Kostyniuk, L.P., St. Louis, R.M., Zanier, N., Eby, D.W., & Molnar, L.J. (2012). *Transportation and Older Adults in Rural Michigan*. Lansing, MI: Michigan Department of Transportation.

- Kozak, K., Pohl, J., Birk, W., Greenburg, J., Artz, B., Blommer, M., Cathey, L., Curry, R. (2006). Evaluation of lane departure warning for drowsy drivers. *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*, **50**, 2400-2404.
- Kramer, A.F., Cassavaugh, N., Horrey, W.J., & Mayhugh, J.L. (2007). Influence of age and proximity warning devices on collision avoidance in simulated driving. *Human Factors*, **49**, 935-949.
- Kusano, K. & Gabler, H.C. (2014). Comprehensive target populations for current active safety systems using national crash databases. *Traffic Injury Prevention*, **15**, 753-761.
- Kusano, K., Gorman, T.I., Sherony, R., & Gabler, H.C. (2014). Potential occupant injury reduction in the U.S. vehicle fleet for lane departure warning-equipped vehicles in single-vehicle crashes. *Traffic Injury Prevention*, **15**, S157-S164.
- Lahausse, J.A., Fildes, B.N., Page, Y., & Fitzharris, M.P. (2008). The potential for automatic crash notification systems to reduce road fatalities. *Annals of Advances in Automotive Medicine - 52nd Annual Scientific Conference*, **52**, 85-92.
- Lai, F. & Carsten, O. (2012). What benefit does Intelligent Speed Adaptation deliver: A close examination of its effect on vehicle speeds. *Accident Analysis & Prevention*, **48**, 4-9.
- Lai, F., Carsten, O., & Tate, F. (2012). How much benefit does Intelligent Speed Adaptation deliver: An analysis of its potential contribution to safety and environment. *Accident Analysis & Prevention*, **48**, 62-73.
- Lai, F. Hjalmdahl, Chorlton, K., & Wiklund, M. (2010). The long-term effect of intelligent speed adaptation on driver behaviour. *Applied Ergonomics*, **41**, 179-186.
- Langford, J., Charlton, J.L., Koppel, S., Myers, A., Tuokko, H., Marshall, S., Man-Son-Hing, M., Darzins, P., Di Stefano, M., & Macdonald, W. (2013). Findings from the Candrive/Ozcandrive study: Low mileage older drivers, crash risk, and reduced fitness to drive. *Accident Analysis & Prevention*, **61**, 304-310.
- Langford, J. & Koppel, S. (2006). Epidemiology of older driver crashes—Identifying older driver risk factors and exposure patterns. *Transportation Research Part F*, **9**, 309-321.
- Langford, J., Methorst, R., & Hakamies-Blomqvist, L. (2006). Older drivers do not have a high crash risk—A replication of low mileage bias. *Accident Analysis & Prevention*, **38**, 574-578.
- Larsen, L. & Kines, P. (2002). Multi-disciplinary in-depth investigations of head on and left turn road collisions. *Accident Analysis & Prevention*, **34**, 367-380.

- Lavallière, M., Reimer, B., Mehler, B., D'Ambrosio, L., Wang, Y., Teasdale, N., & Coughlin, J.F. (2011). The effect of age and gender on visual search during lane changing. In *Proceedings Driving Assessment 2011: 6th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*. Ames Iowa: University of Iowa.
- Lavallière, M., Laurendeau, D., Simoneau, M. & Teasdale, N. (2011). Changing lanes in a simulator: Effects of aging on the control of the vehicle and visual inspection of mirrors and blind spot. *Traffic Injury Prevention*, **12(2)**, 191-200.
- LeBlanc, D.J., Bao, S., Sayer, J.R., & Bogard, S. (2013). Longitudinal driving behavior with integrated crash-warning system. *Transportation Research Record: Journal of the Transportation Research Board*, **2365**, 17-21.
- LeBlanc, D., Sayer, J., Winkler, C., Ervin, R., Bogard, S., Devonshire, J., Mefford, M., Hagan, M., Bareket, Z., Goodsell, R., & Gordon, T. (2006). *Road Departure Crash Warning System Field Operational Test: Methodology and Results*. Report No. UMTRI-2006-9-1. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Lee, J.D., Caven, B., Haake, S., & Brown, T.L. (2001). Speech-based interaction with in-vehicle computer: The effect of speech-based E-mail on drivers' attention to the roadway. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, **43(4)**, 631-640.
- Liu, C., Chen, C, Subramanian, & Utter, D. (2005). *Analysis of Speeding-Related Fatal Motor Vehicle Crashes*. Report N. DOT HS 809 839. Washington, DC: National Highway Traffic Safety Administration.
- Llaneras, R.E., Neurauter, M.L., & Green, C.A. (2011). Factors moderating the effectiveness of rear vision systems: What performance-shaping factors contribute to drivers' detection and response to unexpected in-path obstacles when backing? Report No. 2011-01-0549. SAE Technical Papers.
- Long, G.M. & Crambert, R.F. (1989). The nature and basis of age-related changes in dynamic visual acuity. *Psychology of Aging*, **5**, 138-143.
- Lyman, J.M., McGwin, G, & Sims, R.V. (2001). Factors related to driving difficulty and habits in older drivers. *Accident Analysis & Prevention*, **33**, 413-421.
- Maag, B. & Mark, C. (2012). Assisting drivers' merging onto the motorway: Evaluation of a new advanced driver assistance system (ADAS) using multi-driver simulation. In *Proceedings of the 19th ITS World Congress*. Washington, DC: ITS America.
- Maciej, J. & Vollrath, M. (2009). Comparison of manual vs. speech-based interaction with in-vehicle information systems. *Accident Analysis & Prevention*, **41**, 924-930.

- Malfetti, J.W. (1985). *Needs and Problems of Older Drivers: Survey Results and Recommendations*. Falls Church, VA: AAA Foundation for Traffic Safety.
- Maltz, M. & Shinar, D. (2008). Imperfect in-vehicle collision avoidance warning systems can aid drivers. *Human Factors*, **46**(2), 357-366.
- Marchau, V., van Nes, N., Walta, L., & Morsink, P. (2010). Enhancing speed management by in-car speed assistance systems. *IET Intelligent Transport Systems*, **4**(1), 3-11.
- Marottoli, R.A. & Drickamer, M.A. (1993). Psychomotor mobility and the elderly driver. *Clinical Geriatric Medicine*, **9**, 403-411.
- Marottoli, R.A., Mendes de Leon, C.F., Glass, T.A., Williams, C.S., Cooney, L.M. Jr., Berkman, L.F., & Tinetti, M.E. (1997). Driving cessation and increased depressive symptoms: prospective evidence from the New Haven EPESE. Established populations for epidemiologic studies of the elderly. *Journal of the American Geriatrics Society*, **45**, 202-206.
- Marottoli, R.A., Richardson, E.D., Stowe, M.H., Miller, E.G., Brass, L.M., Cooney, L.M. Jr., & Tinetti, M.E. (1998). Development of a test battery to identify older drivers at risk for self-reported adverse driving events. *American Geriatrics Society Journal*, **46**, 562-568.
- Marshall, D. C., Wallace, R.B., Torner, J.C., & Leeds, M.B. (2010). *Enhancing the Effectiveness of Safety Warning Systems for Older Drivers: Project Report*. Report No. DOT HS 811 417. Washington, DC: National Highway Traffic Safety Administration.
- Marshall, D. C., Wallace, R.B., Torner, J.C., & Leeds, M.B. (2011). Effectiveness of an intersection violation warning system. *Proceedings of the Sixth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, **6**, 555-561.
- Marshall, D.M., Chrysler, S., & Smith, K. (2014). Older Drivers' Acceptance of In-Vehicle Systems and the Effect it has on Safety. Report No. MATC-UI: 217. Lincoln, NE: Mid-America Transportation Center.
- Marshall, P.H., Elias, J.W., & Wright, J. (1985). Age related factors in motor error detection and correction. *Experimental Aging Research*, **11**, 201-206.
- Marshall, S.C., Man-Son-Hing, M., Bédard, M., Charlton, J., Gagnon, S., Gélinas, I., Koppel, S., Korner-Bitensky, N., Langford, J., Mazer, B., Myers, A., Naglie, G., Polgar, J., Porter, M.M., Rapoport, M., Tukko, H., Vrkljan, B., & Woolnough, A. (2013). Protocol for Candrive II/Ozcandrive, a multicentre prospective older driver cohort study. *Accident Analysis & Prevention*, **61**, 245-252.
- Massie, D.L., Campbell, K.L., & Williams, A.F. (1995). Traffic accident involvement rates by driver age and gender. *Accident Analysis & Prevention*, **27**(1), 73-87.

- Mayr, U., Spieler, D.H., & Kliegl, R. (2001). Aging and executive control: Introduction to this Special Issue. *European Journal of Cognitive Psychology*, **13**, 104.
- Mazzae, E.N., Barickman, F., Baldwin, G.H., & Ranney, T. (2008). *On-Road Study of Drivers' Use of Rearview Video Systems (ORS DURVS)*. Report No. DOT HS 811 024. Washington, DC: National Highway Traffic Safety Administration.
- Meyer, J. (2009). Designing in-vehicle technologies for older drivers. *The Bridge: Linking Engineering and Society*, **39(1)**, 21-26.
- McElheny, M., Blanco, M., & Hankey, J.M. (2006). On-road evaluation of an in-vehicle curve warning device. *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*, **50**, 2414-2418.
- McFarland, R.A., Domey, R.G., Warren AB, & Ward, D.C. (1960). Dark adaptation as a function of age: A statistical analysis. *Journal of Gerontology*, **15**, 149-154.
- McLaughlin, D. (2014). 17 ways driverless cars could change America. *The Federalist*. URL: <http://thefederalist.com/2014/07/16/17-ways-driverless-cars-could-change-america/>.
- McLaughlin, S.B., Hankey, J.M., Green, C.A., & Kiefer, R.J. (2003). Driver performance evaluation of two rear parking aids. In *Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles*. Washington, DC: National Highway Traffic Safety Administration.
- McPherson, K., Michael, J., Ostrow, A., & Shafron, P. (1988). *Physical Fitness and the Aging Driver: Phase I*. Washington, DC: AAA Foundation for Traffic Safety.
- McGuckin, N.A. & Srinivasan, N. (2003). *Journey to Work in the United States: 1960 – 2000*. Report No. FHWA-EP-03-058. Washington, DC: Federal Highway Administration.
- McGwin, G. & Brown, D.B. (1999). Characteristics of traffic crashes among young, middle-aged, an older drivers. *Accident Analysis & Prevention*, **31**, 181-198.
- Mehler, B., Kidd, D., Reimer, B., Reagan, I., Dobres, J. & McCartt, A. (2015). *Multi-Modal Assessment of On-Road Demand of Voice and Manual Phone Calling and Voice Navigation Entry across Two Embedded Vehicle Systems*. Arlington, VA: Insurance Institute for Highway Safety.
- Mehler, B., Reimer, B., Dobres, J., McAnulty, H., Mehler, A., Munger, D., & Coughlin, J.F. (2014a). *Further Evaluation of the Effects of a Production Level "Voice-Command" Interface on Driver Behavior: Replication and a Consideration of the Significance of Training Method*. MIT AgeLab Technical Report No. 2014-2. Cambridge, MA: Massachusetts Institute of Technology.

- Mehler, B., Reimer, B., Lavallière, M., Dobres, J., & Coughlin, J.F. (2014b). *Evaluating Technologies Relevant to the Enhancement of Driver Safety*. Washington, DC: AAA Foundation for Traffic Safety.
- Michon, J.A. (1985). A critical view of driver behavior models: What do we know, what should we do? In *Human Behavior and Traffic Safety, Proceedings of a General Motors Symposium on Human Behavior and Traffic Safety*. New York, NY: Plenum Press.
- Molnar, L.J., Charlton, J.L., Eby, D.W., Bogard, S.E., Langford, J., Koppel, S., Kolenic, G., Marshall, S., Man-Son-Hing, M. (2013). Self-regulation of driving by older adults: Comparison of self-report and objective driving data. *Transportation Research Part F*, **20**, 29-38.
- Molnar, L.J. & Eby, D.W. (2009). Getting around: Meeting the boomers' mobility needs. In *Boomer Bust? Economic and Political Issues of the Graying Society*. R. Houston (Ed). Praeger Publishing.
- Mulholland, A. (2009). *Seven New Technologies to Help Older Drivers*. URL: <http://www.ctvnews.ca/seven-new-technologies-to-help-aging-drivers-1.454373>. Toronto Canada: Bell Media.
- National Highway Traffic Safety Administration (2006). *Vehicle Backover Avoidance Technology Study: Report to Congress*. Washington, DC: US Department of Transportation.
- National Highway Traffic Safety Administration (2012). *Speeding*. Report No. DOT HS 812 021. Washington, DC: National Highway Traffic Safety Administration.
- National Highway Traffic Safety Administration (2015). *Vehicles with ESC*. URL: <http://www.safercar.gov/Vehicle+Shoppers/Resources/Vehicles+with+ESC>. Washington, DC: National Highway Traffic Safety Administration. Accessed March, 2015.
- National Institute of Aging (2011). *Global Health and Aging*. NIA Publication No. 11-7737. Washington DC: National Institute of Aging, National Institute of Health.
- Naujoks, F. & Totzke, I. (2014). Behavioral adaptation caused by predictive warning system—The case of congestion tail warnings. *Transportation Research Part F*, **26**, 49-61.
- Navarro, J., Mars, F., & Hoc, J-M. (2007). Lateral control assistance for car drivers: A comparison of motor priming and warning systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, **49**, 950-960.
- Neurauter, M.L., Hankey, J.M., Schalk, T.B., & Wallace, G. (2012). Outbound texting: Comparison of speech-based approach and handheld touch-screen equivalent. *Transportation Research Record*, **2321**, 23-30.

- Novotný, S. & Bouchner, P. (2011). Elderly drivers vs. IVIS and ADAS—Results from a set of driving simulation studies. *Advances in Transportation Studies an International Journal*, **A24**, 23-32.
- Nowakowski, C., Gupta, S. D., Vizzini, D., Sengupta, R., Mannasseh, C., Spring, J., VanderWerf, J. & Sharafsaleh, A. (2011). *SafeTrip 21 Initiative: Networked Traveler Foresighted Driving Field Experiment*. Report No. UCB-ITS-PRR-2011-05. Berkeley, CA: California PATH Program.
- Nowakowski, C., Vizzini, D., Gupta, S.D., & Sengupta, R. (2012). Evaluation of real-time freeway end-of-queue alerting system to promote driver situational awareness. *Transportation Research Record: Journal of the Transportation Research Board*, **2324**, 37-43.
- O'Connor, A. (2013). Would a driverless car be right for you? AARP. URL: <http://www.aarp.org/home-family/getting-around/info-03-2013/driverless-cars-are-we-close.html>.
- Organization for Economic Co-operation and Development (2001). *Ageing and Transport. Mobility Needs and Safety Issues*. Paris: OECD Publications.
- Owsley, C., McGwin, G. Jr., & Seder, T. (2011). Older drivers' attitudes about instrument cluster designs in vehicles. *Accident Analysis & Prevention*, **43**, 2024-2029.
- Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research*, **23**, 689-699.
- Owsley, C., & Sloane, M.E. (1990). Vision and aging. In F. Bolter, & J. Grafman (Eds.), *Handbook of Neuropsychology: Volume 4*. Amsterdam, The Netherlands: Elsevier.
- Oxley, J., Fildes, B., Corben, B., & Langford, J. (2006). Intersection design for older drivers. *Transportation Research Part F*, **9**, 335-346.
- Oxley, P.R., Barham, P.A., & Ayala, B.E. (1995). The use of route guidance systems by elderly drivers. In *Proceedings of the 1994 World Congress on Applications of Transport Telemetrics and Intelligent Vehicle-Highway Systems*. Boston, MA: Artech House.
- Paris, J-C., Bellet, T., Cour, M., Marin-Lamellet, C., Deleurence, P., Moreau, F., Boverie, S., Andre, J-M., & Claverie, B. (2014). *Driving Assurances for Senior Drivers: A Human Centered Design Approach*. Paper No. 18291. Transport Research Arena 2014.
- Parker, D., MacDonald, L, Sutcliffe, P., & Rabbitt, P. (2001). Confidence and the older driver. *Ageing and Society*, **21**, 169-182.
- Perez, M.A., Viita, D., Hankey, J.M., Voran-Nowak, S., & Tengler, S.C. (2011). Voice- and visual-manual-control navigation system evaluation based on user performance in

- destination entry and navigation tasks. In *TRB 90th Annual Meeting Compendium of Papers DVD*. Washington, DC: Transportation Research Board.
- Petrofsky, J.S. & Lind, A.R. (1975). Aging, isometric strength and endurance, and cardiovascular responses to static effort. *Journal of Applied Psychology*, **1**, 91-95.
- Piccinini, G.F.B., Rodrigues, C.M., Leitão, M., & Simões, A. (2014). Driver's behavioral adaptation to Adaptive Cruise Control (ACC): The case of speed and time headway. *Journal of Safety Research*, **49**, 77-84.
- Piccinini, G.F.B., Rodrigues, C.M., Leitão, M., & Simões, A. (2015). Reaction to a critical situation during driving with Adaptive Cruise Control for users and non-users of the system. *Safety Science*, **72**, 116-126.
- Planek, T.W. & Fowler, R.C. (1971). Traffic accident problems and exposure characteristics of the aging driver, *Journal of Gerontology*, **26**, 224-230.
- Ponds, R.W.H.M., Brouwer, W.H., & van Wolffelaar, P.C. (1988). Age differences in divided attention in a simulated driving task. *Journal of Gerontology*, **43**, 151-156.
- Popiv, D., Rommerskirchen, C., Duschl, M., & Rakic, M. (2010). Effects of assistance of anticipatory driving on driver's behaviors during deceleration phases. In *Proceedings of the European Conference on Human Centered Design for Intelligent Transport Systems*. Berlin, Germany: HUMANIST VCE, HUMAN Centered Design for Information Society Technologies Virtual Centre of Excellence.
- Ragland, D.R., Satariano, W.A., & MacLeod, K.E. (2005). Driving cessation and depressive symptoms. *Journal of Gerontology: Medical Sciences*, **60A**, 399-403.
- Rajaonah, B., Anceaux, F., & Vienne, F. (2006). Trust and the use of adaptive cruise control: A study of a cut-in situation. *Cognition, Technology, and Work*, **8**, 146-155.
- Rakha, H., Hankey, J., Patterson, A. & van Aerde, M. (2001). Field evaluation of safety impacts of adaptive cruise control. *ITS Journal*, **6(3)**, 225-259.
- Ranney, T.A., Mazzae, E.N., Baldwin, G.H.S., & Salaani, M.K. (2007). *Characteristics of Voice-Based Interfaces for In-Vehicle Systems and Their Effects on Driving Performance*. Report DOT HS 810 867. Washington, DC: National Highway Traffic Safety Administration.
- Raytheon Commercial Infrared and EICAN-Teaxs Optical Technology. (2000). *NightDriver™ Thermal Imaging Camera and HUD Development Program for Collision Avoidance Applications*. Report DOT-HS-809-163. Washington, DC: US Department of Transportation.
- Reagan, I.J. & Bliss, J.P. (2013). Perceived mental workload, trust, and acceptance resulting from exposure to advisory and incentive based intelligent speed adaptation systems. *Transportation Research Part F*, **21**, 14-29.

- Reagan, I.J., Bliss, J.P., van Houten, R., & Hilton, B.W. (2013). The effects of external motivation and real-time automated feedback on speeding behavior in a naturalistic setting. *Human Factors*, **55**(1), 218-230.
- Regan, M.A., Mitsopoulos, E., Haworth, N. & Young, C. (2002). *Acceptability of In-Vehicle Intelligent Transport Systems to Victorian Car Drivers*. Report No. 02/02. Melbourne, Australia: Monash University Accident Research Centre.
- Regan, M.A., Young, K.L., Triggs, T.J., Tomasevic, N., Mitsopoulos, E., Tierney, P., Healy, D., Tingvall, C. & Stephan, K. (2006). Impact on driving performance of intelligent speed adaptation, following distance warning and seatbelt reminder systems: key findings from the TAC safecar project. *Intelligent Transport Systems, IEE Proceedings*, **153**(1), 51-62.
- Reimer, B. (2104). Driver assistance systems and the transition to automated vehicles: A path to increase older adult safety and mobility? *Public Policy and Aging Report*, **24**, 27-31.
- Reimer, B., Mehler, B. & Coughlin, J.F. (2010). *An Evaluation of Driver Reactions to New Vehicle Parking Assist Technologies Developed to Reduce Driver Stress*. Cambridge, MA: New England University Transportation Center, Massachusetts Institute of Technology.
- Reimer, B., Mehler, B., McAnulty, H. Munger, D., Mehler, A., Perez, E.A.G., Manhardt, T., & Coughlin, J.F. (2013). A preliminary assessment of perceived and objectively scaled workload of a voice-based driver interface. In *Proceedings of the 7th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*. Ames, IA: University of Iowa.
- Rudin-Brown, C.M & Parker, H.A. (2004). Behavioural adaptation to adaptive cruise control (AC): Implications for preventive strategies. *Transportation Research Part F*, **7**, 59-76.
- Rumar, K. (2002). *Night Vision Enhancement Systems: What Should They Do and What More Do We Need to Know?* Report No. UMTRI-2002-12. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Rusch, M.L., Schall, M.C.Jr., Lee, J.D., Dason, J.D., & Rizzo, M. (2014). Augmented reality cues to assist older drivers with gap estimation for left-turns. *Accident Analysis & Prevention*, **71**, 210-221.
- Sakakibara, K. & Tsugawa, S. (2013). Merging assistance at an expressway ramp with vehicle-to-vehicle communications. In *Proceedings of the 20th ITS World Congress*. Washington, DC: ITS America.
- Salthouse, T.A. (1987). Adult age differences in integrative spatial ability. *Psychology & Aging*, **2**, 254-260.

- Salthouse, T.A., Mitchell, D.R., Skovronek, E., & Babcock, R.L. (1989). Effects of adult age and working memory on reasoning and spatial ability. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **15**, 507-516.
- Santos, A., McGuckin, N., Nakamoto, H.Y., Gray, D., & Liss, S. (2011). *Summary of Travel Trends: 2009 National Household Travel Survey*. Report No. FHWA-PL-11-022. Washington, DC: Federal Highway Administration.
- Sayer, J.R., Buonarosa, M.J., Bao, S., Bogard, S.E., LeBlanc, D.J., Blankespoor, A.D., Funkhouser, D.S., & Winkler, C.B. (2010). *Integrated Vehicle-Based Safety Systems Light-Vehicle Field Operational Test Methodology and Results Report*. Report No. UMTRI-2010-30. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Seppelt, B.D. & Lee, J.D. (2007). Making adaptive cruise control (ACC) limits visible. *International Journal of Human-Computer Studies*, **65**, 192-205.
- Seto, Y., Sugano, T., Gokan, T., Sakui, H., Akatsu, Y., & Kobayashi, M. (2012). Development of a backup collision intervention system. In *Proceedings of the 19th Intelligent Transport Systems World Congress*. Washington, DC: ITS America.
- Scialfa, C.T., Kline, D.W., & Lyman, B.J. (1987). Age differences in target identification as a function of retinal location and noise level: Examination of the useful field of view. *Psychology & Aging*, **2**, 14-19.
- Schieber, F., Hiris, E., White, J., Williams, M., & Brannan, J. (1990). Assessing age-differences in motion perception using simple oscillatory displacement versus random dot cinematography. *Investigative Ophthalmology & Visual Science*, **S31**, 355.
- Schieber, F., Kline, D.W., Kline, T.J.B., & Fozard, J.L. (1992). *The Relationship Between Contrast Sensitivity and the Visual Problems of Older Drivers* (SAE Technical Paper No. 920613). Warrendale, PA: Society of Automotive Engineers, Inc.
- Schreiner, C., Blanco, M., & Hankey, J.M. (2004). Investigation of driving behavior changes associated with manual and voice-activated phone-dialing in a real-world environment. In *Proceedings 14th Annual Meeting and Exposition ITS America*. Washington, ITS America.
- Sekuler, R. & Ball, K. (1986). Visual localization: Age and practice. *Journal of the Optical Society of America*, **3**, 864-867.
- Seville, L.R. (2014). *Aging Tsunami: In Montana, Aging in Place Takes a Village*. URL: <http://www.nbcnews.com/health/health-care/aging-tsunami-montana-aging-place-takes-village-n267081>. NBC News.

- Shaw, L., Polgar, J.M., Vrkljan, B., & Jacobson, J. (2010). Seniors' perceptions of vehicle safety risks and needs. *The American Journal of Occupational Therapy*, **64(2)**, 215-224.
- Shepard, R.J. (1998). Aging and exercise. In T.D. Fahey (Ed.), *Encyclopedia of Sport Medicine and Science*. URL: <http://sportssci.org>.
- Sihvola, N., Luoma, J., Schirokof, A., Salo, J., & Karkola, K. (2009). In-depth evaluation of the effects of an automatic emergency call system on road fatalities. *European Transport Research Review*, **1(3)**, 99-105.
- Simões, A. & Pereira, M. (2009). Older drivers and new in-vehicle technologies: Adaptation and long-term effects. In M. Kurosu (Ed.) *Human Centered Design*. Berlin: Springer-Verlag.
- Siskind, V., Steinhardt, D., Sheehan, M., O'Connor, T., & Hanks, H. (2011). Risk factors for fatal crashes in rural Australia. *Accident Analysis & Prevention*, **43**, 1082-1088.
- Sivak, M., Campbell, K.L., Schneider, L.W., Sprague, J.K., Streff, F.M., & Waller, P.F. (1995). The safety and mobility of older drivers: What we know and promising research issues. *UMTRI Research Review*, **26(1)**, 1-21.
- Sivak, M., Flannaagan, M.J., Traube, E.C., Aoki, M., & Sayer, J.R. (1994). *Evaluation of an Active Headlight System*. Report No. UMTRI-94-17. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Sivak, M. & Schoettle, B. (2011). *Recent Changes in the Age Composition of Drivers in 15 Countries*. Report No. UMTRI-2011-43. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Sivinski, R. (2011). *Crash Prevention Effectiveness of Light-Vehicle Electronic Stability Control: An Update of the 2007 NHTSA Evaluation*. Report No. DOT HS 811 486. Washington, DC: National Highway Traffic Safety Administration.
- Spyropoulou, I.K., Karlaftis, M.G., & Reed, N. (2014). Intelligent Speed Adaptation and driving speed: Effects of different system HMI functionalities. *Transportation Research Part F*, **24**, 39-49.
- Ståhl, A., Oxley, P., Berntman, M., & Lind, L. (1994). The use of vision enhancements to assist elderly drivers. In *Towards an Intelligent Transport System: Proceedings of the First World Congress on Applications of Transport Telematics and Intelligent Vehicle-highway Systems*. London, England: Artech House.
- Stalvey, B.T. & Owsley, C. (2000). Self-perceptions and current practices of high-risk older drivers: Implications for driver safety interventions. *Journal of Health Psychology*, **5(4)**, 441-456.

- Stamatiadis, N. (1996). Gender effect on the accident patterns of elderly drivers. *The Journal of Applied Gerontology*, **15**, 8-22.
- Stanton, N.A. & Young, M.S. (2005). Driver behavior with adaptive cruise control. *Ergonomics*, **10**, 1294-131.
- Staplin, L., Gish, K.W., & Joyce, J. (2008). "Low mileage bias" and related policy implications—A cautionary note. *Accident Analysis & Prevention*, **40**, 1249-1252.
- Staplin, L., Gish, K.W., & Sifrit, K.J. (2014). Using cognitive status to predict crash risk: Blazing new trails? *Journal of Safety Research*, **48**, 19-25.
- Staplin, L., Lococo, K.H., McKnight, A.J., McKnight, A.S., & Odenheimer, G.L. (1998). *Intersection Negotiation Problems of Older Drivers, Volume II: Background Synthesis on Age and Intersection Driving Difficulties*. Report No. DOT HS 808 850. Washington, DC: US Department of Transportation.
- Staplin, L., Lococo, K.H., Stewart, J., & Decina, L. (1999). *Safe Mobility for Older People: Notebook* (Report No. DOT HS 808 853). Washington, DC: National Highway Traffic Safety Administration.
- Strand, N., Nilsson, J., Karlsson, I.C.M., & Nilsson, L. (2011). *Interaction with and Use of Driver Assistance Systems: A Study of End-User Experiences*. In Proceedings of the 18th ITS World Congress. Washington, DC: ITS America.
- Strayer, D.L., Cooper, J.M., Turrill, J., Coleman, J., Mederios-Ward, N., & Biondi, F. (2013). *Measuring Cognitive Distraction in the Automobile*. Washington, DC: AAA Foundation for Traffic Safety.
- Strayer, D.L., Turrill, J., Coleman, J.R., Ortiz, E.V., & Cooper, J.M. (2014). *Measuring Cognitive Distraction in the Automobile II: Assessing In-Vehicle Voice-Based Interactive Technologies*. Washington, DC: AAA Foundation for Traffic Safety.
- Stutts, J., & Martell, C. (1992). Older driver population and crash involvement trends, 1974–1988. *Accident Analysis & Prevention*, **24(4)**, 317-327.
- Stutts, J., Martell, C., & Staplin, L. (2009). *Identifying Behaviors and Situations with Increased Crash Risk for Older Drivers*. Report No. DOT HS 811 093. Washington, DC: National Highway Traffic safety Administration.
- Sullivan J.M, Bärgrman, J., Adachi, G. & Schoettle, B. (2004). *Driver Performance and Workload Using a Night Vision System*. Report No. UMTRI-2004-8. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Sullivan, J.M. & Flannagan, M.J. (2007). Determining the potential safety benefits of improved lighting in three pedestrian crash scenarios. *Accident Analysis & Prevention*, **39**, 638-647.

- Suzuki, K. & Jansson, H. (2003). An analysis of driver's steering behaviour during auditory or haptic warnings for the designing of lane departure warning system. *JSAE Review*, **24**, 65-70.
- Szanton, S.L., Seplaki, C.L., Thorpe, R.J., Allen, J.K., & Fried, L.P. (2010). Socioeconomic status is associated with frailty: The Women's Health and Aging Studies. *Journal of Epidemiology and Community Health*, **64**, 63-67.
- Tachibana, H. (2011). The development of a parking support system considering driving characteristics. In *Proceedings of the SAE 2011 World Congress and Exhibition*. Warrendale, PA: SAE International.
- Tefft, B.C. (2014). *Prevalence of Motor Vehicle Crashes Involving Drowsy Drivers, United States 2009-2013*. Washington, DC: AAA Foundation for Traffic Safety.
- The Hartford (2012). *Top Technologies for Mature Drivers: Expert Ranking*. URL: <http://www.thehartford.com/mature-market-excellence/vehicle-technology>. Hartford, CT: The Hartford Financial Services Group, Inc.
- Totzke, I., Jessberger, S., Mühlbacher & Krüger, H-P. (2011). Semi-autonomous advanced parking assistants: Do they really have to be learned if steering is automated? *IET Intelligent Transport Systems*, **5(2)**, 141-147.
- Totzke, I., Müehlbacher, & Krüger, H-P. (2010). Semi-autonomous advanced parking assist: A source of drivers' distraction? In *Human Factors: A System View of Human, Technology and Organization: Annual Conference of the Europe Chapter of the Human Factors and Ergonomics Society*. Santa Monica, CA: Human Factors and Ergonomics Society.
- Totzke, I., Naujoks, F., Mühlbacher, & Krüger, H-P. (2011). Precision of congestion warnings: Do drivers really need warnings with precise information about the congestion tails position. In D.de Waard, N. Merat, A.H. Jamson, Y. Bernard, O.M.J. Carsten (Eds.), *Human Factors of Systems and Technology*. Maastricht, The Netherlands: Shaker Publishing.
- Trübswetter, N. & Bengler, K. (2013). Why should I use ADAS? Advanced driver assistance systems and the elderly: knowledge, experience, and usage barriers. *Proceedings of the Seventh International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*. Ames, IA: University of Iowa.
- University of Michigan Transportation Research Institute (2015). *Curve-Speed Warning Systems*. URL: <http://www.umtri.umich.edu/our-focus/curve-speed-warning-systems>. Ann Arbor, MI: University of Michigan Transportation Research Institute.
- Van Driel, C.J.G., Hoedemaeker, M., & van Arem, B. (2007). Impacts of a congestion assistant on driving behavior and acceptance using a driving simulator. *Transportation Research Part F*, **10**, 139-152.

- Vlassenroot, S., Broekx, S., De Mol, J., Panis, L.I., Brijs, T., & Wets, G. (2007). Driving with intelligent speed adaptation: Final results of the Belgian ISA-trial. *Transportation Research Part A*, **41**, 267-279.
- Vlassenroot, S., Brookhuis, K., Marchau, V., & Witlox, F. (2010). Towards defining a unified concept for the acceptability of Intelligent Transport Systems (ITS): A conceptual analysis based on the case of Intelligent Speed Adaptation (ISA). *Transportation Research Part F*, **13**, 164-178.
- Vrkljan, B.H. & Polgar, J.M. (2007). Driving, navigation, and vehicular technology: Experiences of older drivers and their co-pilots. *Traffic Injury Prevention*, **8**, 403-410.
- Walker, R., Stevens, A., Anjum, O., Suriarachchi, M., & McNamara, K. (2010). Benefits of automatic crash notification for traffic management. In *Proceedings IET Road Transport Information and Control Conference and the ITS United Kingdom Members' Conference (RTIC 2010) - Better transport through technology*. New York, NY: IEEE.
- Wall, J., Cuenca, V., Creef, K., & Barnes, B. (2013). Attitudes and opinions towards Intelligent Speed Adaptation. In *Proceedings of the 2013 IEEE Intelligent Vehicles Symposium (IV)*. New York, NY: IEEE.
- Warner, H.W., Özkan, T., & Lajunen. (2010). Drivers' propensity to have different types of intelligent speed adaptation installed in their cars. *Transportation Research Part F*, **3**, 206-214.
- West, R.L., Crook, T.H., & Barron, K.L. (1992). Everyday memory performance across the life-span: effects of age and noncognitive individual differences. *Psychology & Aging*, **7**, 72-82.
- Wheaton, A.G., Chapman, D.P., Presley-Cantrell, L.R., Croft, J.B., & Roehler, D.R. (2013). Drowsy Driving—19 States and the District of Columbia. *Morbidity and Mortality Weekly Report*, **61(51-52)**, 1033-1037.
- Williams, L.E. (2002). *Emergency Vehicle Automatic Crash Notification & Event Reporting Technology*. Aliso Viejo, CA: Roadside Telematics Corporation.
- Williamson, A. & Chamberlain, T. (2005). *Review of On-Road Driver Fatigue Monitoring Devices*. Kensington, New South Wales: NSW Injury Risk Management Research Centre, University of New South Wales.
- Windsor, T., Anstey, K., Butterworth, P., Luszcz, M., & Andrews, G. (2007). The role of perceived control in explaining depressive symptoms associated with driving cessation in a longitudinal study. *The Gerontologist*, **47(2)**, 215-223.
- Wolf, E. (1960). Glare and age. *Archives of Ophthalmology*, **64**, 502-514.

- Wu, J., Subramanian, R., Craig, M., Starnes, M., & Longthorne, A. (2013). The effect of earlier or automatic collision notification on traffic mortality by survival analysis. *Traffic Injury Prevention*, **14**, S50-S57.
- Xiong, H. Boyle, L.N., Moeckli, J., Dow, B.R., & Brown, T.L. (2012). Use patterns among early adopters of adaptive cruise control. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, **54**, 722-733.
- Yang, J, & Coughlin, J.F. (2014). In-vehicle technology for self-driving cars: Advantages and challenges for aging drivers. *International Journal of Automotive Technology*, **15(2)**, 333-340.
- Yunkyung, J., Gruenewald, T.L., Seeman, T.E., & Sarkisian, C.A. (2010). Productive activities and development of frailty in older adults. *Journal of Gerontology: Biological Sciences and Social Sciences*, **65B(2)**, 256-261.
- Zelazo, P.D., Craik, F.I.M., & Booth, L. (2004). Executive function across the life span. *Acta Psychologica*, **115**, 167-183.
- Zhang, L., Wang, B., Jia, H., & Dong, B. (2012). Study on the adaptability of on-board navigation equipment for older drivers. In *CICTP 2012*. Warrendale, PA: SAE International.
- Ziefle, M., Pappachan, P., Jakobs, E-M., & Wallentowitz, H. (2008). Visual and auditory interfaces of advanced driver assistance systems for older drivers. *ICCHP 2008*, **5105**, 62-69.