Fifty Years of Driving Safety Research

John D. Lee

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John D. Lee, University of Iowa, Iowa City, Iowa

Objective: This brief review covers the 50 years of driving-related research published in *Human Factors,* its contribution to driving safety, and emerging challenges. **Background:** Many factors affect driving safety, making it difficult to assess the impact of specific factors such as driver age, cell phone distractions, or collision warnings. **Method:** The author considers the research themes associated with the approximately 270 articles on driving published in *Human Factors* in the past 50 years. **Results:** To a large extent, current and past research has explored similar themes and concepts. Many articles published in the first 25 years focused on issues such as driver impairment, individual differences, and perceptual limits. Articles published in the past 25 years address similar issues but also point toward vehicle technology that can exacerbate or mitigate the negative effect of these issues. Conceptual and computational models have played an important role in this research. **Conclusion:** Improved crashworthiness has contributed to substantial improvements in driving safety over the past 50 years, but future improvements will depend on enhancing driver performance and perhaps, more important, improving driver behavior. Developing models to guide this research will become more challenging as new technology enters the vehicle and shifts the focus from driver performance to driver behavior. **Application:** Over the past 50 years, *Human Factors* has accumulated a large base of driving-related research that remains relevant for many of today's design and policy concerns.

Driving is central to the lives and deaths of many. Cars represent more than transportation, particularly in the United States, where cars provide autonomy and freedom. Licensure is a rite of passage for young adults, and losing a license can jeopardize the independent living of older people.

In 2000, worldwide traffic fatalities totaled 1,259,898 and were the ninth most common cause of death (Peden, McGee, & Krug, 2002). In the United States alone, more than 40,000 people die in motor vehicle crashes each year, making it the most common cause of death for those between 4 and 35 years of age (National Center for Statistics and Analysis [NCSA], 2004). Fortunately, driving safety has improved substantially over the past 50 years, with fatalities in the United States dropping from 7.24 per million miles traveled in 1950 to 1.53 in 2000. Some of this reduction reflects improvements in crashworthiness and a better understanding of how the human body interacts with the vehicle interior during crashes, a topic covered in an early issue of the journal (Severy, 1961). Although driving safety has made impressive gains, these improvements lag behind those in commercial aviation, and the United States, once a leader in driving safety, now lags behind many other countries (Evans, 2004). Because the physics of collisions limit the benefits of increased crashworthiness, future safety improvements depend on improving drivers' ability to avoid collisions – the focus of most driving-related articles published in *Human Factors* from the beginning (Forbes, 1960).

Approximately 10% (270 articles) of all articles published in *Human Factors* address driving and driving safety. Figure 1 shows that the number of articles per year increased substantially in the mid-1970s, when there was a general realization that human behavior played a critical role in driving safety. The landmark Indiana Tri-Level study (Treat

Address correspondence to John D. Lee, Department of Mechanical and Industrial Engineering, University of Iowa, 2130 Seamans Ctr., Iowa City, IA 52242; jdlee@engineering.uiowa.edu. ***HUMAN FACTORS,*** Vol. 50, No. 3, June 2008, pp. 521–528. DOI 10.1518/001872008X288376.

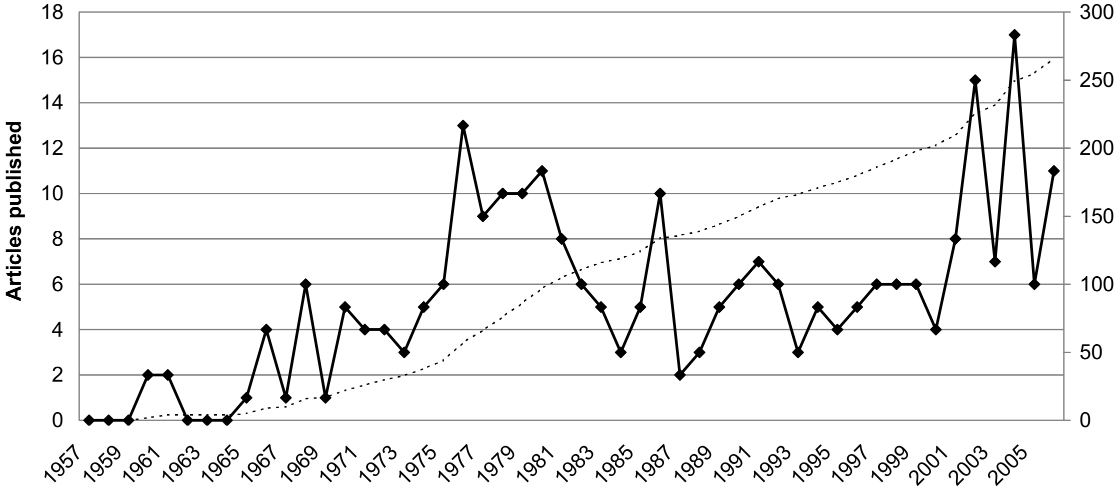

Figure 1. Cumulative and yearly number of articles published from 1957 to 2006 that address driving performance and safety.

et al., 1979) identified driver error as a contributing factor in approximately 90% of crashes, and several other reports confirmed the central role driver behavior plays in driving safety (Fell, 1976; McDonald, 1977). The past 5 years have also seen a substantial increase in driving-related articles as emerging technology either threatens to distract drivers (e.g., cell phones) or promises to enhance safety (e.g., collision warning systems). This article highlights only a few findings and general themes associated with these articles. A more thorough treatment of these issues can be found in recent reviews and books (Dewar & Olson, 2007; Elvik & Vaa, 2005; Fuller & Santos, 2002; Groeger, 2000; Lee, 2006; Shinar, 2007).

Table 1 lists the most frequently cited driving-related *Human Factors* articles published in the past 26 years. These articles reflect enduring challenges facing the profession but also point toward emerging research issues. The articles reveal a strong focus on individual differences, impairment, perceptual capabilities, and in-vehicle technology. The emphasis on individual differences and impairment reflects diversity not seen in other human factors domains, such as military aviation. Driving involves a heterogeneous population acting in varied environments, often with diverse goals. An 85-year-old woman traveling on a two-lane rural road to get groceries represents a very different safety problem than a 16-year-old driving friends through town with no particular place to go. As a consequence, in contrast to military aviation and other highly constrained domains, driving safety depends more on behavior than on performance.

In driving, performance is different from behavior. Behavior reflects the choices people make regarding goals, priorities, performance trade-offs, and acceptable safety margins, whereas performance reflects perceptual, cognitive, and motor control capacities. Performance reflects a person's capability in a certain environment, whereas behavior is that person's actual actions in the same environment as they are mediated by the person's goals, needs, and motivation (Naatanen & Summala, 1976). Because driving safety depends on factors that affect both behavior and performance, the journal contains articles addressing a wide diversity of human factors considerations, from individual differences in risk-taking propensity to motor control. Models of driver performance have successfully described how many perceptual and motor limits influence driving performance, but models of driver behavior still await development.

INDIVIDUAL DIFFERENCES

The driving population is extremely varied, and age is one difference that has a tremendous effect on crash rates. On a per-mile basis, young drivers ages 16 to 19 are overrepresented in severe crashes by a factor of 10 compared with adult drivers ages 40 to 50 (McKnight & McKnight, 2003). The large number of fatalities among young drivers is

TABLE 1: Driving-Related Articles With More Than Three Citations per Year Published in the Past 26 Years (Years 1981 and 2006 Inclusive Based on ISI Data as of September 21, 2007)

Article	Total Citations	Citations per Year
Brown, I. D. (1994). Driver fatigue. *Human Factors, 36,* 298–314.	78	5.57
Ball, K., & Owsley, C. (1991). Identifying correlates of accident involvement for the older driver. *Human Factors, 33,* 583–595.	98	5.47
Wood, J. M. (2002). Age and visual impairment decrease driving performance as measured on a closed-road circuit. *Human Factors, 44,* 482–494.	26	5.20
Strayer, D. L., & Drews, F. A. (2004). Profiles in driver distraction: Effects of cell phone conversations on younger and older drivers. *Human Factors, 46,* 640–649.	15	5.00
Roenker, D. L., Cissell, G. M., Ball, K. K., Wadley, V. G., & Edwards, J. D. (2003). Speed-of-processing and driving simulator training result in improved driving performance. *Human Factors, 45,* 218–233.	24	4.80
Summala, H., & Mikkola, T. (1994). Fatal accidents among car and truck drivers: Effects of fatigue, age, and alcohol consumption. *Human Factors, 36,* 315–326.	66	4.71
Lee, J. D., Caven, B., Haake, S., & Brown, T. L. (2001). Speech-based interaction with in-vehicle computers: The effect of speech-based e-mail on drivers' attention to the roadway. *Human Factors, 43,* 631–640.	26	4.33
Fairclough, S. H., & Graham, R. (1999). Impairment of driving performance caused by sleep deprivation or alcohol: A comparative study. *Human Factors, 41,* 118–128.	36	4.00
Horrey, W. J., & Wickens, C. D. (2006). Examining the impact of cell phone conversations on driving using meta-analytic techniques. *Human Factors, 48,* 196–205.	7	3.50
Lee, J. D., McGehee, D. V., Brown, T. L., & Reyes, M. L. (2002). Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator. *Human Factors, 44,* 314–334.	19	3.17
Shinar, D., & Schieber, F. (1991). Visual requirements for safety and mobility of older drivers. *Human Factors, 33,* 507–519.	53	3.13

particularly tragic because it represents so many years of life lost (Evans, 1991). Drivers older than age 80 are also overrepresented in crashes, by a factor of approximately 5, compared with drivers ages 40 to 50 (Bedard, Guyatt, Stones, & Hirdes, 2002). However, several biases may inflate the fatal crash risk of older drivers: Older drivers are more frail and so are more likely to die if they crash (Evans, 1991); older drivers also tend to drive less than younger drivers, and across all ages, those who drive less per year have a greater risk per mile driven (Hakamies-Blomqvist, Raitanen, & O'Neill, 2002; Langford, Methorst, & Hakamies-Blomqvist, 2006). Adjusting for these biases greatly diminishes the overrepresentation of older drivers in crashes. The crash risk of older drivers represents a concern because the number of drivers older than age 65 will increase by 70% between 1996 and 2030 (Lee, 2006).

The aging process diminishes the visual capacity of drivers and can contribute to crash likelihood (Booher, 1978); however, visual performance has a surprisingly weak effect on crash risk because drivers often adapt their behavior and drive safely (Olson & Farber, 2003). Isolating the age-related cognitive impairments that govern crash risk has been a topic of considerable research reported in *Human Factors* (Ball & Owsley, 1991). Discerning differences in information processing and attentional capacity represents a promising way to identify at-risk drivers (Avolio, Kroeck, & Panek, 1985; Ball, Owsley, Sloane, Roenker, & Bruni, 1993). One consistent finding is that diminished selective attention and slower information processing are associated with greater crash risk. Preliminary evidence suggests that speed-of-processing training can mitigate some age-related risk (Roenker, Cissell, Ball, Wadley, & Edwards, 2003).

Although young drivers perform better than older drivers on visual and motor skill tasks, they crash more frequently, which may reflect underdeveloped hazard perception skills. The most cited article published in *Human Factors* concerning driving safety showed that inexperienced drivers scan the road differently than experienced drivers do (Mourant & Rockwell, 1972, cited 112 times as of September 21, 2007), which influences their steering control in that inexperienced drivers depend on foveal vision to guide their lateral control (Smiley, Reid, & Fraser, 1980; Summala, Nieminen, & Punto, 1996). A recent examination of driver eye movements confirms these findings by showing that the eye movements of inexperienced drivers focus more on guiding lateral control than on hazard detection, leading to diminished hazard awareness that may increase novice drivers' crash risk (Pradhan et al., 2005). Training can affect the pattern of eye movements and enhance hazard awareness (Pollatsek, Narayanaan, Pradhan, & Fisher, 2006). Beyond hazard awareness, other factors, such as risk-taking tendency and time-sharing ability, contribute to the high crash rates of novice drivers (Deery & Fildes, 1999).

Several individual differences beyond driver age and experience may also contribute to crash risk. Although difficult to modify through training, individual differences in attitudes (Schuster, 1970) and risk-taking propensity (Deery & Fildes, 1999) may influence driving safety. A long series of articles have shown that individual differences in cognitive style, as measured by field dependence, influence crash risk and driving performance, with field-dependent drivers crashing more frequently (Goodenough, 1976), scanning less effectively (Shinar, 1978), and missing more targets in cluttered scenes (Ward, Parkes, & Crone, 1995).

Individual differences, such as cognitive style and age-related cognitive slowing, have a complicated effect on driving safety that makes data interpretation and risk assessment difficult. Individual differences can affect driving performance, but often drivers adapt their behavior and drive safely. For example, older drivers might curtail driving at night and in heavy traffic. Conversely, young drivers, who may be unaware of certain driving hazards, behave in a way that jeopardizes driving safety. How drivers adapt their behavior has a strong influence on how individual differences influence driving safety.

IMPAIRMENT: ALCOHOL, FATIGUE, AND DISTRACTION

Research has clearly established that alcohol and fatigue impair performance and undermine driving safety (Huntley & Centybear, 1974). From 1982 to 2001, alcohol impairment contributed to 43% of all traffic fatalities, declining from 56% in 1982 to 36% in 2001 (Cummings, Rivara, Olson, & Smith, 2006). Fatigue represents a less prominent safety problem that may be underreported because, unlike with alcohol, no forensic test can measure its presence. Researchers attribute between 2% and 25% of car crashes (I. D. Brown, 1994) and more than 50% of truck crashes (Bonnet & Arand, 1995) to fatigue. Controlled studies have shown that fatigue-related impairments share some similarities with those of alcohol. Drivers deprived of sleep the previous night suffered decrements in lane-keeping performance similar to the performance declines of drivers with a blood alcohol content of 0.07% (Fairclough & Graham, 1999). Twenty-four hours of sustained wakefulness undermined performance on a tracking task to a degree similar to that of a blood alcohol content of 0.10% (Dawson & Reid, 1997).

Recently, distraction has emerged as an important impairment that may also undermine driving safety, a topic addressed in a recent special issue of *Human Factors* (Lee & Strayer, 2004). Rapidly evolving information technology is increasingly being placed in the vehicle and represents a potential source of distraction. A substantial number of articles are being published on this topic, as reflected by the high frequency of citations for three recent articles in Table 1 (Horrey & Wickens, 2006; Lee, Caven, Haake, & Brown, 2001; Lee, McGehee, Brown, & Reyes, 2002). The meta-analysis of Horrey and Wickens (2006) summarizes 47 articles and finds that cell phone conversations increased drivers' reaction to hazards by an average of 130 ms. This may contribute to the 12% to 25% of crashes that are attributed to driver distraction or inattention (Stutts, Reinfurt, Staplin,

& Rodgman, 2001; Sussman, Bishop, Madnick, & Walter, 1985; Wang, Knipling, & Goodman, 1996).

To a large extent, the degree to which impairment influences driving performance reflects driver behavior–drivers choose to compromise their ability to drive safely by driving while impaired. As a consequence, influencing driver response to impairments may require cultural changes regarding norms of acceptable behavior, which has occurred to some degree with alcohol (Bonnet & Arand, 1995).

LIMITS OF PERCEPTION AND ATTENTION

Many of the most influential articles in *Human Factors* have focused on driver performance associated with limits of attention and perception. This research has made great contributions to understanding how drivers respond to characteristics of the roadway, traffic control devices, and other vehicles. Early research showed that drivers' perceptual limits and reaction times interact with roadway characteristics to influence traffic flow (Forbes, 1960) and that sign and traffic signal design influence how quickly drivers can respond (Ben-Bassat & Shinar, 2006; Cole & Brown, 1968; Dewar, Ells, & Mundy, 1976; Harte, 1975).

Research concerning visual performance associated with judging headways and detecting deceleration of vehicles ahead has a long history and continued importance because rear-end collisions still account for nearly a third of all crashes (National Safety Council, 1996). Early research in *Human Factors* helped to characterize drivers' perceptual sensitivity to lead vehicle deceleration (Hoffmann, 1966; Mortimer, 1971; Torf & Duckstein, 1966). Drivers often maintain headways that are too short to allow for adequate braking in response to unexpected braking of the car ahead (Ben-Yaacov, Maltz, & Shinar, 2002; Taieb-Maimon & Shinar, 2001). These perceptual thresholds and the relationship between driver reaction time, vehicle separation, and lead vehicle acceleration play an important role in defining effective collision warning systems (T. L. Brown, Lee, & McGehee, 2001; Kiefer, Flannagan, & Jerome, 2006).

When crashes do occur, they are often not caused by perceptual thresholds; rather, drivers fail to look at the right thing at the right time. Even if they look in the right direction, the cognitive demands of a competing activity can interfere with detecting safety-critical changes (McCarley et al., 2004). Although driving often leaves people with spare attentional capacity, this capacity can be severely limited relative to the periodically intense demands of driving (Moray, 1990; Senders, Kristofferson, Levison, Dietrich, & Ward, 1967). Even a simple tracking task can interfere with sign detection (Noble & Sanders, 1980), and relatively brief glances away from the road can increase brake reaction time (Zhang, Smith, & Witt, 2006) and crash risk (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006).

VEHICLE TECHNOLOGY

Many years of research have explored ways of compensating for drivers' perceptual and attentional limits. Because rear-end collisions are relatively common and often could be avoided by a faster response, many researchers have considered how to accentuate the perceptual cues that specify the slowing behavior of a lead vehicle. Some have shown a benefit of brake light enhancements that indicate that the lead vehicle is coasting (Mortimer, 1971), that the driver of the lead vehicle has rapidly released the accelerator (Shinar, 2000), or that the driver ahead is braking hard (Mortimer & Kupec, 1983). Of these efforts to accentuate the driver's perception of a braking lead vehicle, the high-mounted brake light has become standard on all production vehicles, but the performance benefits seen in controlled studies have not resulted in the expected safety benefits (Sivak, Post, Olson, & Donohue, 1981; Theeuwes & Alferdinck, 1995).

Substantial research has also considered how to help drivers avoid collisions by bringing information about potential collision situations into the drivers' own cars. Some systems help drivers maintain safer following distances (Dingus, McGehee, Manakkal, & Jahns, 1997; Shinar & Schechtman, 2002), and others warn them when an imminent collision looms (Lee et al., 2002; Maltz & Shinar, 2004). Although collision warning systems help drivers by warning them of specific collision situations, they can also help by encouraging them to adopt safer following distances. In one study, drivers exposed to a rear-end collision warning system maintained longer headways for at least 6 months after a relatively brief exposure to the system (Ben-Yaacov et al., 2002).

Beyond collision warnings, other vehicle technology, such as adaptive cruise control, navigation systems, and electronic stability control, is becoming common. Such systems automate elements of driving and change the task dramatically, as anticipated by Sheridan (1970) more than 25 years ago. The chronicle of the high-mounted brake light demonstrates that even if these systems improve driver performance, they may not always improve driving safety. Drivers sometimes adapt their behavior to undermine the benefit of a safety system (Wilde, 1976, 1982), for example, by driving faster when equipped with studded snow tires (Rumar, Berggrund, Jernberg, & Ytterbom, 1976). But in other situations, such as with seat belts, drivers using the safety equipment do not drive more recklessly and so enjoy a large safety benefit (Evans, Wasielewski, & von Buseck, 1982).

The ultimate benefit of emerging vehicle automation will depend on how drivers adapt their behavior to the new systems. Poorly designed systems could lead drivers to overrely on the automation and engage in risky behavior (e.g., read e-mail messages while driving because they assume the collision warning system will alert them to the need to intervene). The most effective technology may be that which monitors driver state and driving behavior and helps attend to the roadway and recognize unsafe behavior (Donmez, Boyle, & Lee, 2006; Donmez, Boyle, Lee, & Scott, 2007). The ability of such technology to detect aberrant driving behavior and share this information not only with the driver, but with other drivers, parents, insurance companies, and police might dramatically change driving behavior.

MODELS OF DRIVER PERFORMANCE AND BEHAVIOR

Both conceptual and computational models have played a strong role in guiding and cumulating the results of research published in *Human Factors*. Sheridan's (1970) conceptual model of driving as a control task at three different time scales provides a useful description of how drivers adapt to new technologies and roadway demands (Allen, Lunenfeld, & Alexander, 1971; Michon, 1985). Control at the short timescale is dominated by performance limits, whereas strategic control at the longer timescale is dominated by the attitudes that guide behavior. Many articles have described quantitative models of drivers' longitudinal control performance in following other vehicles (Bekey, Burnham, & Seo, 1977) and their lateral control performance in negotiating curves and maintaining lane position (McRuer, Allen, Weir, & Klein, 1977). Such models not only are useful for assessing design alternatives but can also play a central role in data interpretation (Weir & McRuer, 1973). As an example, one model of curve negotiation led to novel measures of driver lane-keeping performance – namely, time-to-line crossing (Godthelp, 1986; Godthelp, Milgram, & Blaauw, 1984). More recent conceptual models (Sheridan, 2004; Young & Stanton, 2002) and computational models (Salvucci, 2006; Schweickert, Fisher, & Proctor, 2003) help address the challenges associated with emerging vehicle automation and distracting infotainment systems.

An important challenge for these modeling techniques is in capturing how new technology influences driver behavior. The protective influence of technology could be great if drivers relied on it appropriately, but the same technology could undermine safety if used inappropriately (Parasuraman & Riley, 1997). Initial research has shown that drivers tend to underestimate the actual risk of failure of systems that serve communication functions and that such systems' controllability and observability govern risk judgments (MacGregor & Slovic, 1989). As automotive technology becomes less observable and less directly controllable, drivers may misestimate the risk of a failure and rely on the technology inappropriately (Lee & See, 2004). Developing conceptual and computational models of driver reliance on automation and adaptation to technology is critical in shaping future vehicle technology to the needs of drivers.

CONCLUSION

The past 50 years have seen substantial improvements in driving safety, often as a result of improved crashworthiness and passive safety systems, such as airbags. Future improvements depend on enhancing driver performance and behavior so drivers avoid crashes. Active safety systems, which include collision warnings and electronic stability control, promise substantial safety benefits by enhancing driver performance. However, these benefits will be realized only if drivers rely on these systems appropriately and if these systems help drivers behave more safely. Likewise, responding to persistent safety problems, such as alcohol, fatigue, and the emerging problem of distraction, will require systems that improve driver behavior. A shift in societal norms with regard to what constitutes acceptable behavior substantially reduced alcohol-related crashes, and a similar response may be needed to address dangerous driver behavior associated with fatigue and distraction, as well as to further reduce alcohol-related crashes. Technology, particularly that which monitors driver behavior and shares this information, could play an important role in changing norms and the driving culture (Moeckli & Lee, 2006).

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John D. Lee is a professor in the Department of Mechanical and Industrial Engineering at the University of Iowa and is the director of human factors research at the National Advanced Driving Simulator. He received his Ph.D. in mechanical engineering from the University of Illinois in 1992.

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