CHAPTER 4

Driving Safety

By John D. Lee

Driving is a common and hazardous activity that is a prominent cause of death worldwide. Driver behavior represents a predominant cause, contributing to over 90% of crashes. In this review, I will focus on how driver behavior influences driving safety by describing the types of crashes and their general causes, the driving process, the perceptual and cognitive characteristics of drivers, and driver types and impairments. Evidence from each of these perspectives suggests that breakdowns of a multilevel control process are the fundamental factors that undermine driving safety. Drivers adapt and drive safely in a broad range of situations but fail when expectations are violated or when feedback is inadequate. The review concludes by considering driving safety from a societal risk management perspective.

Driving has become an essential part of millions of people's lives. From 1980 to 2000 the number of licensed drivers in the United States increased 23.7% to a total of 191 million. This increase reflects both a growing population and a growing percentage of licensed drivers, which has increased from 57% in 1950 to 88% in 2000. Paralleling these trends, the number of miles driven has also grown substantially, from 458 billion miles annually in 1950 to 2.767 trillion miles in 2000. Between 1990 and 2000 alone, total miles traveled grew by 28.9% (U.S. Department of Transportation, 2000). Although these and other statistics cited in this review are for the United States, unless otherwise noted, many of these trends are consistent around the world.

Safety and Demographic Trends

With more people driving more miles, the number of fatalities has also increased. However, the number of fatalities per mile driven has decreased. In 1950 there were 7.24 fatalities per 100 million miles driven compared with 1.53 in 2000. This equates to a total of 33 186 motor vehicle-related fatalities in 1950 compared with 42 387 in 2000.

Although fatalities have decreased by 78.9% on a per-mile basis, the cost of motor vehicle crashes remains substantial—it was recently estimated at $432 billion per year (Wang, Knipling, & Blincoe, 1999). In 2000 worldwide traffic fatalities totaled 1,259,898, making vehicular crashes the ninth most common cause of death (Peden, McGee, & Krug, 2002). In the United States crashes are the most common cause of death for people between 4 and 34 years old (Subramanian, 2005).

The fatality rate is not uniformly distributed around the world. The United States has 0.19 fatalities per 1000 vehicles compared with 1.9 per 1000 for Egypt (Evans, 2004). Figure 4.1 shows that the fatality rate climbs to more than 10 per 1000 vehicles in several African countries and approaches 100 per 1000 in Mozambique, where for every 10 cars, approximately 1 person dies in a motor vehicle crash each year. Consistent with Smeed's law (Smeed, 1949), the rate of crashes declines as the number of vehicles per person increases.

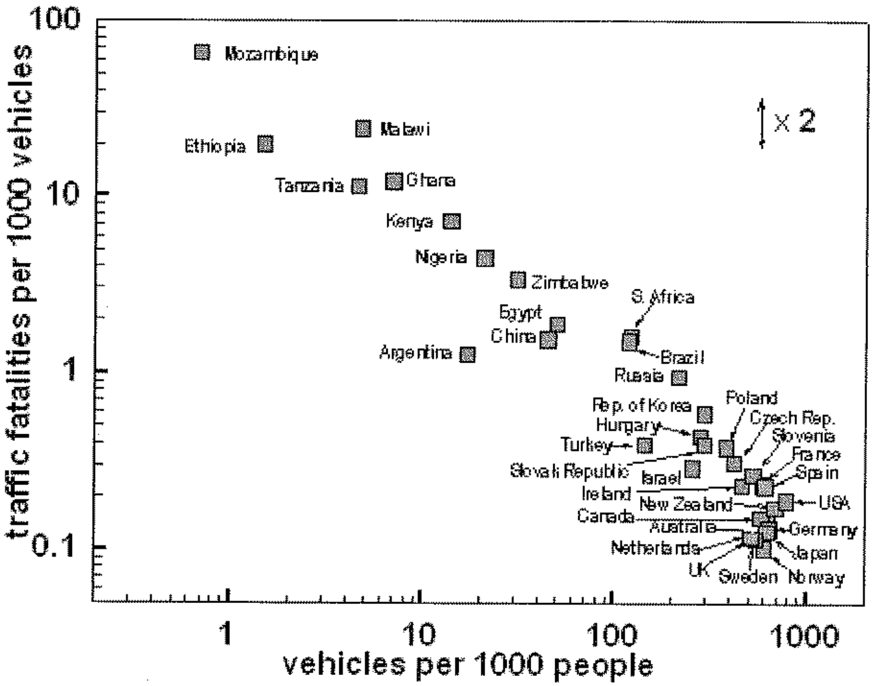

Figure 4.1. Traffic fatalities for selected countries (Evans, 2004). Reproduced with permission from Evans L., Traffic Safety *(2004), Bloomfield, MI: Science Serving Society. © Leonard Evans.*

To place the human cost of crashes in context, each day in 2002 in the United States, an average of 16.3 people between the ages of 13 and 19 died in crashes, more than the 14 who died in the Columbine High School tragedy. Each month more people died in crashes than the total killed in the terrorist attack of September 11, 2001. As of 2003, the number of people who had died in motor vehicle crashes (3 240 140) was nearly five times the total number of American troops lost in every war from the Revolutionary War through the Iraq conflict (650 000; see Evans, 2004). Driving constitutes an underappreciated international health problem.

Crashes and the associated injuries and deaths disproportionately affect younger and older drivers. On a per-mile basis, young drivers aged 16 to 19 are overrepresented in severe crashes by a factor of 10 compared with adult drivers aged 40 to 50 (McKnight & McKnight, 2003). The large number of fatalities among young drivers is particularly costly to society in that it represents a disproportionate number of preretirement years of life lost (Evans, 1991). Although the statistics are not as dramatic as those for younger drivers, drivers over the age of 80 are also overrepresented in crashes by a factor of approximately five compared with drivers aged 40 to 50 (Bedard, Guyatt, Stones, & Hirdes, 2002). The contribution of older drivers to driving-related incidents will increase as the number of older drivers increases. Demographic trends suggest that the proportion of drivers over the age of 65 will increase by 70.3% between 1996 and 2030. Because driving is such a central part of most people's lives, curtailing driving privileges based on age may severely limit mobility and erode quality of life. Increasing driving safety for younger drivers and preserving the safe mobility of older drivers are particularly important challenges.

Safety and Technology Trends

Powerful technology trends may exacerbate or mitigate the risk of driving, particularly for younger and older drivers. Emerging sensor, wireless, and computing technology supports an increasingly diverse array of innovations that may dramatically affect driving safety. Those technologies that promise to enhance safety include collision warning devices, antilock braking systems (ABS), airbags, and automatic aid request systems (Lee & Kantowitz, 2005; Pauzie, 1995). At the same time, cellular phones, in-vehicle Internet access, satellite radio, and DVD players may work to undermine driver safety (Lee & Strayer, 2004). Even technologies that aim to enhance safety, such as ABS and airbags, can sometimes undermine it (Broughton & Baughan, 2002; Sagberg, Fosser, & Saetermo, 1997). Younger and older drivers may benefit most from the new safety systems, but they are also most vulnerable to poorly implemented technology (Dingus, Hulse, et al., 1997; McKnight & McKnight, 1993).

Implementing technology to enhance driving safety requires careful attention to the distinction between driver performance and driver behavior. Driver performance reflects both the capabilities of the driver in maintaining control of the vehicle and avoiding hazardous situations as well as drivers' perceptual and cognitive limits. In contrast, behavior reflects how drivers choose to respond to situations and risks they are willing to accept. For example, driving performance describes how closely a driver can maintain a particular speed, whereas behavior has to do with the speed that the driver chooses to maintain. The distinction between performance and behavior has important implications for interpreting crash data, conducting controlled experiments, and developing technology to enhance driving safety.

In this review I consider research addressing driver performance and behavior conducted between 1995 and 2004, but the review also includes particularly influential earlier research. After describing types of crashes and their general causes, I will consider driver behavior and performance in the context of driving as a multilevel control activity. The perceptual and cognitive characteristics of drivers help explain why this control activity breaks down and crashes result. Next, I discuss driver types and impairments and their contribution to crash rates. Strategies to improve driving safety are considered from the perspective of the driver, the vehicle, and the roadway infrastructure. The review concludes with a discussion of driving safety from a risk management perspective.

A theme running throughout this review is the challenge of how to coordinate the various strands of technology development to enhance rather than degrade driving safety. This focus leaves many critical issues for future reviews in this area. Several particularly important aspects of vehicle safety that are not covered by this review include vehicle and roadway lighting, sign visibility and design, traffic engineering, and roadway design. This review focuses on driver characteristics and how they interact with technology to influence road safety. In driving, as in other domains, technology often promises benefits that fail to materialize and, in some instances, can even undermine safety.

CRASH TYPES, CONSEQUENCES, AND CAUSES

One of the fundamental challenges in improving driving safety is to understand the causes and consequences of crashes. Unlike controlled studies of driving performance, crash data reflect the full array of factors that contribute to driving safety. Unfortunately, this complex array of factors makes it difficult to determine what particular factors contribute to a crash. Yet, even with this limit, analysis of crash data provides a useful first step in identifying how various factors, such as driver age, contribute to driving safety.

Like failures in any complex system, a motor vehicle crash typically represents a confluence of events that conspire to undermine behaviors that might not otherwise interfere with a typical drive (Reason, 1990). Looking away from the road for a second or two to adjust the radio is a routine event, but when combined with a patch of ice and a lead vehicle that unexpectedly slows, it can become a deadly one. Crashes typically result from several contributing factors rather than a single cause. In addition, post hoc interpretations of crashes are vulnerable to the influence of the particular perspective of the investigators identifying the causes (Rasmussen, 1990). As a result, designating driver error or any particular driver behavior, such as speeding or inattention, as the cause of a crash oversimplifies the situation.

Drivers are responsible for avoiding many crashes, but driver error is considered a predominant contributor to crashes. The Indiana Tri-Level Study, one of the most intensive analyses of crash causes, found that driver errors contributed to 92.9% of all crashes compared with 34.9% for roadway factors and 9.1% for vehicle factors (Treat et al., 1979). Table 4.1 shows the distribution of causes underlying driver error and identifies problems of attention and distraction as contributing to 47% of crashes, which are highlighted in bold. Improper lookout represents a particularly common problem and reflects a failure to scan the environment properly and the tendency to look in the right direction but not see critical events. A recent report showed that driver factors continue to be much more prevalent than roadway or vehicle factors in contributing to crashes (U.S. General Accounting Office, 2003). Overall, driver performance and behavior play a dominant role in motor vehicle safety.

Crash Types and Distributions

The difference between fatal and nonfatal crashes represents a fundamental distinction regarding crash types. Because nonfatal crashes occur so frequently, their economic cost exceeds that of fatal crashes, and so both merit attention (Blincoe et al., 2002). Fatal crashes tend to involve single vehicles, occur at night in rural areas, and often

TABLE 4.1: Possible Driver-Related Contributions to Crashes (Treat et al., 1979)

Possible Cause	*Percentage**
Improper lookout	*23.0*
Excessive speed	16.9
Inattention	*15.0*
Improper evasive action	13.3
Internal distraction	*9.0*
Improper driving technique	9.0
Inadequately defensive driving technique	8.8
False assumption	8.3
Improper maneuver	6.2
Overcompensation	6.0

**Total more than 100% because multiple causes can contribute to any particular crash. Problems associated with driver attention and distraction are shown in italics.*

involve alcohol and high speeds. In contrast, nonfatal crashes tend to involve more than one vehicle, occur during commuting time in urban areas, do not involve alcohol, and involve relatively low speeds. Somewhat different causal mechanisms contribute to fatal and nonfatal crashes.

Crashes vary systematically according to the time of day, time of year, and age of the driver. Not surprisingly, fatigue-related crashes depend on the time of day (Pack et al., 1995). The distribution of crashes attributed to fatigue peaks in the early morning hours and again in the early afternoon (Horne & Reyner, 1995). Crashes also depend on the time of year, but not as might be expected. Figure 4.2 shows higher fatal crash rates in the summer and lower crash rates in the months of February, March, and April. Interestingly, this effect is apparent for northern states but not for southern states, suggesting that weather does not directly contribute to the overall driving safety problem, as might be expected (Evans, 2004). Drivers adapt to weather and other factors, often with counterintuitive consequences. Whether or not a crash occurs depends on road conditions, traffic, and how drivers adapt to the situation.

Figure 4.3 shows that crashes also depend on driver age and gender. Older and younger drivers are overrepresented. However, older drivers tend to drive much less than younger drivers and so are overrepresented to a lesser degree. Figure 4.4, which considers crash rates per mile driven, indicates that younger and older drivers are both substantially overrepresented and that young males are particularly vulnerable. Although older and younger drivers share a similar degree of risk, different factors contribute to their vulnerability. Likewise, the types of crashes that comprise the peaks during the day and year suggest that diverse mechanisms underlie crash involvement, such as fatigue-related crashes in the early morning hours. Crash scenarios, such as intersection collisions or rear-end collisions, identify the range of situations that result in crashes and suggest the underlying mechanisms responsible for them.

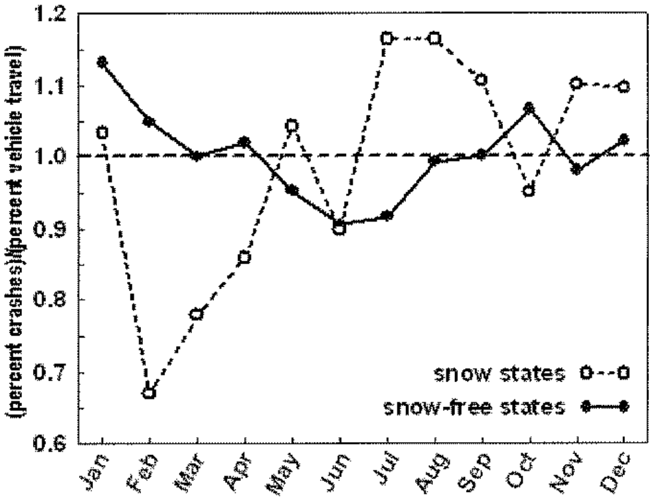

Figure 4.2. *Fatal crash rate as defined by the percentage of crashes divided by the percentage of vehicle miles traveled. Reproduced with permission from Evans L.,* Traffic Safety *(2004). Bloomfield, MI: Science Serving Society. © Leonard Evans.*

Predominant Crash Types and Their Causes

Considering the crash scenario helps identify breakdowns in vehicle control that contribute to crashes. Rear-end collisions, which are the most frequent type of crash, accounting for nearly 30% of all crashes, represent a breakdown in hazard detection and longitudinal control. Crashes of this type are caused by distraction and drivers' tendency to follow too closely. In contrast, roadway departure crashes, which cause the greatest number (over 40%) of driving-related fatalities, result from a failure of lateral control, often associated with excessive speed (National Safety Council, 1996). Intersection collisions—in particular left-turn-across-path crashes—represent an important crash type in which older drivers are overrepresented (Keskinen, Ota, & Katila, 1998; Preusser, Williams, Ferguson, Ulmer, & Weinstein, 1998). Because the crash scenario describes the kinematics of the crash, it is only indirectly linked to underlying driver performance and behavioral factors that contribute to crashes and so does not provide a definitive way to understand crashes.

Crash types are often used to identify mitigation strategies, such as rear-end collision and road departure warning systems. The severity and prevalence of each crash type are critical inputs in calculating the potential benefits of crash mitigation strategies (Wang, Knipling, & Blincoe, 1999). Table 4.2 summarizes the frequency and severity of major crash types between 1989 and 1993 (Wang, Knipling & Blincoe). Overall, rear-end collisions, single-vehicle road departure crashes, and intersection crashes account for over 60% of all motor vehicle crashes (Parker, West, Stradling, & Manstead, 1995).

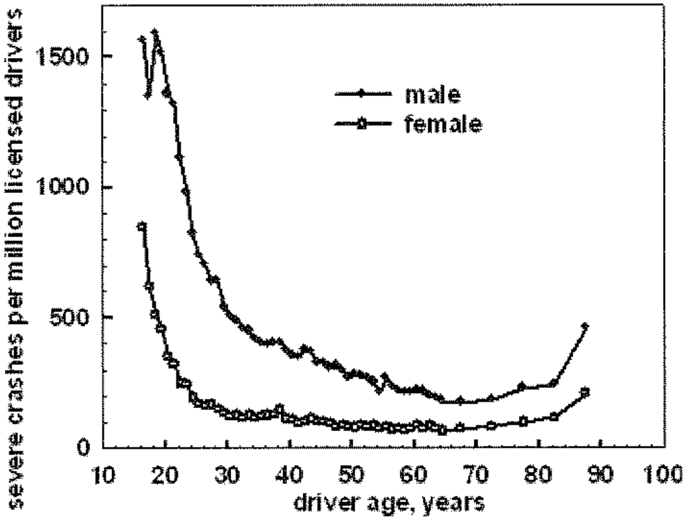

Figure 4.3. *Number of severe crashes for younger and older male and female drivers. Reproduced with permission from Evans L.,* Traffic Safety *(2004), Bloomfield, MI: Science Serving Society. © Leonard Evans.*

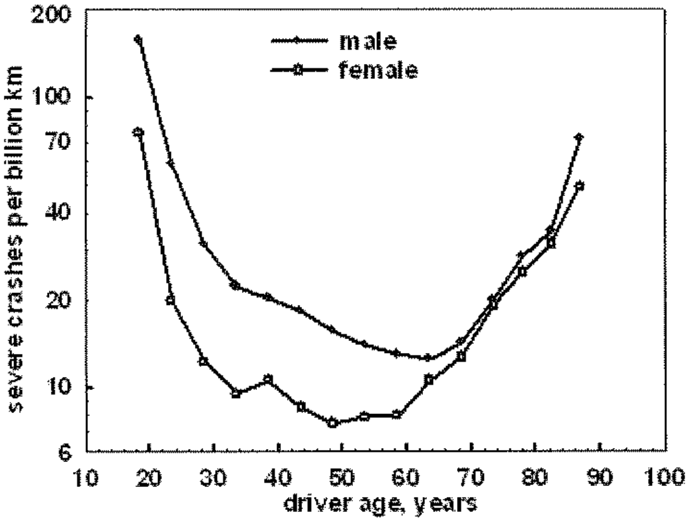

Figure 4.4. *Rate of severe crashes for younger and older male and female drivers. Reproduced with permission from Evans L.,* Traffic Safety *(2004), Bloomfield, MI: Science Serving Society. © Leonard Evans.*

A similar crash typology divides crashes into five categories (Massie, Campbell, & Blower, 1993). The first, single-vehicle nonintersection, is similar to the single-vehicle roadway departure crash category in Table 4.2. The second and third categories encompass crashes at signalized and nonsignalized intersections, respectively. The fourth cat-

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TABLE 4.2: Frequency and Severity of Major Crash Types (Wang et al., 1999)

Crash Type	*Frequency, Number per Year, and Percentage of Total*	*Severity, Economic Cost per Year**
Rear-end	1 454 000 (23%)	$33.8B
Single-vehicle, roadway departure	1 310 000 (21%)	$33.2B
Intersection	899 000 (14%)	$27.4B
Left turn across path	396 000 (6%)	$11.9B
Lane change/merge	234 000 (4%)	$4.1B
Opposite direction	190 000 (3%)	$12.7B
Pedestrian	176 000 (3%)	$9.7B
Backing	171 000 (3%)	$2.4B
Total	6,261,000 (100%)	$164.4B

**The total of $164.4 billion rises to $432 billion per year when derived valuations of loss of life and pain and suffering are included.*

turns across traffic predominate. The fifth category describes vehicles traveling in the same direction, and rear-end collisions predominate.

Yet another three-part typology divides crashes into (a) rear-end collisions; (b) right-of-way violations, often associated with intersections; and (c) loss-of-control crashes, most frequently associated with roadway departures (Parker, West, et al., 1995). Excessive speed—an important contributor to crashes—contributes to several of these crash types, illustrating that no single typology provides a definitive way of categorizing crashes (Blincoe et al., 2002), though many share the basic distinctions shown in Table 4.2.

These crash types provide a first step toward understanding the causal factors that underlie the crash distributions associated with time of year, time of day, and driver age and gender. Categories such as rear-end collision, single-vehicle roadway departure, and intersection collision not only describe the physical mishap but can also begin to identify the factors that cause the crash.

Different contributing factors are related to different crash categories. For example, the causes of rear-end collisions tend to differ from those of intersection collisions. Specifically, driver inattention has been identified as a contributing factor in over 60% of rear-end collisions (Knipling et al., 1993). Distraction is a much less prevalent factor in other crash types. These data suggest that rear-end collisions result from perceptual or attentional failures in detecting a hazard presented by unexpectedly slow-moving or stopped vehicles.

Another contributor to rear-end collisions is the tendency of some drivers to follow too closely relative to the time required to respond safely to a braking lead vehicompensate for the short headways, compared with those who adopt longer headways (Taieb-Maimon & Shinar, 2001), and they are generally more likely to crash (Evans & Wasielewski, 1982; Rajalin, Hassel, & Summala, 1997). Distraction and the tendency to adopt unsafe headways represent important contributors to rear-end collisions.

A very different constellation of factors contributes to roadway departure crashes. In these crashes, fatigue plays an important role. Single-vehicle roadway departure crashes comprise the majority of crashes (78% of the total) in which the driver was judged to have fallen asleep (Pack et al., 1995); 62% of these crashes occurred at speeds in excess of 50 mph. In addition, younger drivers are particularly vulnerable to roadway departure crashes (Ryan, Legge, & Rosman, 1998), especially during their first few months of driving (Mayhew, Simpson, & Pak, 2003). This suggests that the ability to anticipate, judge, and slow for curves is an important contributor to roadway departure crashes. A risk-taking tendency also contributes to drivers' failure to slow sufficiently for curves (McGwin & Brown, 1999; Parker, West, et al., 1995). Lack of experience, a lifestyle that often involves disrupted sleep, and a tendency toward greater risk-taking all make young drivers—especially males—particularly vulnerable to the factors that contribute to roadway-departure crashes.

Younger drivers are overrepresented in roadway departure crashes, whereas older drivers are overrepresented in intersection crashes (McGwin & Brown, 1999). Specifically, the risk of crashing in an intersection is 2.26 times as large for drivers aged 65 to 69 as for drivers aged 40 to 49, whereas the crash risk for drivers aged 65 to 69 is 1.29 times as large for all crash types (Preusser, Williams, et al., 1998). Drivers older than 85 have an even greater risk—10.62 times as large for intersection crashes, but only 3.74 times greater risk for all other crash types—when compared with drivers aged 40 to 49.

The risk for older drivers is particularly high for unsignalized intersections (Preusser, Williams, et al., 1998). At intersections without traffic signals, older drivers who crash tend to stop and then crash into others as they make a turn, whereas younger drivers tend to crash into others because they intentionally fail to stop (Massie et al., 1993). A similar pattern occurs with signalized intersections. Approximately 260,000 crashes are associated with drivers' running red lights, resulting in 750 fatalities each year (Retting, Ulmer, & Williams, 1999). Most red light–runners are younger male drivers who have had prior traffic violations and/or who are likely to be driving while intoxicated (Retting et al., 1999).

Each of these major crash types illustrates some of the failures that undermine driving safety and show that driving is a complex, multilevel control activity that can fail for many reasons. Perceptual limits, attentional demands, violation of expectations, risk-taking, and impairments caused by factors such as alcohol and fatigue all differentially contribute to crash types. Violation of expectations regarding lead vehicle speed and distractions contributes to rear-end collisions. Older drivers are particularly vulnerable to the perceptual and attentional demands of intersections, whereas younger drivers are vulnerable to the effects of fatigue and risk-taking associated with roadway departure and some intersection crashes (Massie et al., 1993; Ryan et al., 1998). Overall, risk-taking, lack of skill, and poor judgment undermine the safety of young drivers, whereas diminished perceptual and attentional capacity affect the safety of older drivers (McGwin & Brown, 1999). Definitions of crash types focus on the trajectory of the vehicle and begin to describe how vehicle control breaks down, but a more detailed description of driver performance and behavior is needed to develop effective crash mitigation strategies (Summala, 1996).

Several conclusions emerge from a consideration of crash types and their distribution:

- Although assessing causation of crashes is somewhat problematic, driver behavior contributes to over 90% of all motor vehicle crashes.
- Fatal crashes and nonfatal crashes reflect substantially different causes and circumstances.
- Crash types based on vehicle kinematics provide a useful first step in understanding how driver performance and behavior contribute to road safety.
- Very generally, rear-end collisions reflect distraction, road departure crashes reflect driver impairment and misjudgments of hazards, and intersection crashes reflect limits of attention.
- A process description of driving as a multilevel control task is needed to better understand crash causes and to develop effective mitigation strategies.

DRIVING AS A MULTIOBJECTIVE, MULTILEVEL CONTROL TASK

The range of crash types and causes reflects the diverse elements of the driving task. Driving is not a homogeneous activity governed by a simple set of human performance limits; it is a complex multilevel control task. Several influential researchers from the 1930s through the 1960s provided the foundation for describing driving as a multilevel control task. Gibson and Crooks (1938) showed how vehicle control depends on the capabilities of the vehicle-driver combination relative to the driving environment. Senders, Kristofferson, Levison, Dietrich, and Ward (1967) described how drivers balance looking at the roadway with looking away from the roadway. McRuer, Allen, Weir, and Klein (1977) provided a control-theoretic description of driver performance. Each of these perspectives still exerts substantial influence on current driving safety research, and each helps answer the general question: Why do drivers crash?

Field Theory of Driving

Gibson and Crooks described driving in terms of a field of safe travel in which drivers adjust their speed and direction to avoid hazards and move themselves toward their destination. The roadway and other vehicles define the field of safe travel, which consists of the possible unimpeded paths the car may take (Gibson & Crooks, 1938). Drivers steer the vehicle toward the center of the field of safe travel, but they do not seek to maintain a specific trajectory, only one that is satisfactorily safe.

The field of safe travel also influences vehicle speed. The minimum stopping zone defines the distance required for the driver to stop the car, and drivers decelerate proportionally to the degree that the stopping zone approaches the end of the field of safe travel. The ratio of the depth of the field of safe travel to the minimum stopping zone

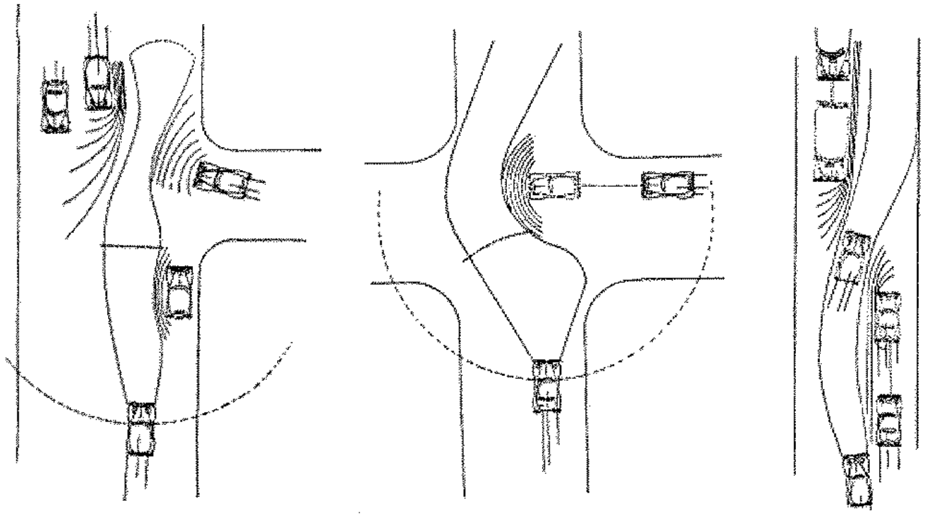

Figure 4.5. *Driving as negotiating a field of safe travel. Reprinted from* American Journal of Psychology, *51, Gibson, J. J. and Crooks, L. E. , A theoretical field-analysis of automobile driving, 453-471, copyright (1938), with permission from University of Illinois Press.*

defines the index of cautiousness. When drivers are in a hurry, the index of cautiousness decreases, and they accept smaller safety margins.

Figure 4.5 shows several scenarios in which the location and direction of other vehicles influence the field of safe travel. Here driving is described as an interaction between perceptual cues and vehicle dynamics for avoiding obstacles while moving toward a destination.

This early perspective on driving generated several important insights that remain relevant in describing driver behavior. First, driver and vehicle characteristics cannot be considered separately. Drivers adapt to improved braking and steering systems with increased speed and closer following distances. Better brakes may decrease the minimum stopping zone, but drivers may increase their speed to maintain a constant index of cautiousness. The concepts of risk homeostasis and behavioral adaptation that describe how drivers adapt to vehicle and roadway improvements share some similarities with this basic perspective (Wilde, 1988, 1989).

Second, Gibson and Crooks (1938) recognized that adverse weather, heavy traffic, or sharp curves are dangerous only to the degree to which they lead drivers to misperceive a field of safe travel or minimum stopping zone. Roadway conditions do not jeopardize driving safety directly; they affect safety only when drivers fail to adapt.

Third, this perspective leads to a description of hazards and driver responses in terms of driver/vehicle capabilities relative to the proximity of hazards. Such time-based descriptions of driving behavior have also emerged through consideration of driving as an intermittent sampling process.

Intermittent Sampling Description of Driving

The field-theoretic description of driving developed by Gibson and Crooks implies that drivers continuously attend to the roadway. Unfortunately, the large number of distraction-related crashes shows that this is not the case. Drivers adjust and listen to the radio, talk to passengers, and interact with an increasingly complex range of technology while driving. As a result, rather than giving the driving task their undivided attention, drivers intermittently sample the roadway. A series of experiments and a mathematical model quantified this phenomenon (Senders et al., 1967).

On a closed section of highway, Senders et al. examined how well people could drive when they wore a helmet with a visor that periodically occluded the forward view. They found that people could drive with surprisingly short and infrequent glances at the roadway. A quantitative sampling model described this behavior by assuming that uncertainty regarding the state of the roadway accumulates between samples (Senders et al.). When uncertainty exceeds a certain threshold, the driver samples the roadway. Experimental data show these assumptions to be reasonable and indicate that drivers are generally well calibrated regarding the buildup of uncertainty relative to vehicle dynamics and roadway characteristics.

The intermittent sampling model continues to influence research addressing the visual demand of in-vehicle systems. Wierwille (1993) described a sampling model that begins when the driver initiates an in-vehicle task by glancing away from the road. Uncertainty builds as the driver's eyes remain off the road, and he or she quickly feels pressured to look toward the forward scene. If the glance to the in-vehicle location exceeds approximately 1.5 seconds and the information cannot be extracted, the driver will look toward the forward scene and try again later. Additional samples are handled in the same way, until all required information is obtained. The rate of uncertainty growth depends on the roadway situation. Curves and complex roadway situations, such as traffic, increase the uncertainty quickly and require more closely spaced samples.

The time-based description of uncertainty accumulation also inspired several models of curve negotiation and car following. For example, time to lane crossing (TLC) provides a direct estimate of the amount of time a driver has available before departing the lane or roadway (Godthelp, Milgram, & Blaauw, 1984). Most simply, TLC is calculated by dividing the distance to the lane boundary by the lateral speed of the vehicle; other formulations consider roadway curvature (van Winsum, Brookhuis, & de Waard, 2000). Drivers tend to maintain a constant TLC over a range of curve radii (van Winsum & Godthelp, 1996). TLC defines a safety margin that drivers maintain by adjusting the speed of the vehicle—those who steer less precisely negotiate curves more slowly.

In a car-following situation, two time-based measures—time to collision (TTC) and time headway—independently influence driver behavior. TTC is calculated by dividing the distance between the vehicles by the relative velocities of the vehicles. Time headway is the distance between the vehicles divided by the velocity of the following vehicle and reflects the time required for the following vehicle to match the deceleration of the lead vehicle. TTC guides the response to dangerous situations by triggering and modulating braking behavior, and time headway guides the response to potentially dangerous situations by modulating how closely drivers follow. A driver will tend to adopt a constant time headway over a range of speeds (van Winsum & Godthelp, 1996).

Understanding how drivers respond to changes in TTC and time headway may be critical if drivers are to use new technology such as adaptive cruise control effectively (Goodrich & Boer, 2003). The time-based description of vehicle state relative to other vehicles and the roadway has substantially influenced the description of vehicle control.

Control-Theoretic Description of Driving

Control-theoretic models represent another long-standing description of driving behavior (McRuer et al., 1977; Weir & McRuer, 1973), which describe driver behavior in terms of control actions used to adjust the state of the vehicle in response to perturbations. For example, drivers adjust the angle of the steering wheel in response to wind gusts and curves in the road; they adjust the accelerator and brake pedals in response to hills and changes in speed limits. Driving behavior represents a combination of feedback and feed-forward control. With feedback control, drivers respond to discrepancies between the vehicle state and the intended state; by adjusting the steering wheel, they can bring a drifting car back toward the center of the road. With feed-forward control, drivers respond to anticipated discrepancies based on an internal model that predicts the future state of the vehicle. A simple example is drivers' use of road curvature to anticipate required steering input. Feed-forward control provides a formal description of how expectations influence driver behavior.

Several recent quantitative models of driver performance include control-theoretic concepts to model steering and speed control performance. These models explain the effect of distractions (Salvucci, 2001; Salvucci & Macuga, 2002) and road geometry (Levison, Bittner, Campbell, & Schreiner, 2002) on driving performance.

Other researchers have used control theory as the basis for conceptual models, such as the influence of distraction on driving performance (Sheridan, 2004). One of the most pervasive examples of this is the multilevel control framework (Allen, Lunenfeld, & Alexander, 1971; Michon, 1985; Ranney, 1994; Summala, 1996). According to this perspective, driving consists of several qualitatively different interacting control activities (see Figure 4.6). These activities differ according to the time scale of control, with moment-to-moment control of the vehicle occurring at a time scale of seconds and higher-level control (e.g., regarding trip planning and adjustments to general driving style) occurring at a time scale of hours or months.

The general multilevel control concept has been used to explain the crash risk of young drivers (Laapotti, Keskinen, Hatakka, & Katila, 2001; Moller, 2004); to characterize the role of cognitive, personality, and social factors in crashes (Lawton & Parker, 1998); and to structure computational models of driver behavior (Al-Shihabi & Mourant, 2003). Recently, multilevel control frameworks such as this have been adopted to describe the effect on driving safety of introducing new technology (Hollnagel, Nabo, & Lau, 2003; Poysti, Rajalin, & Summala, 2005).

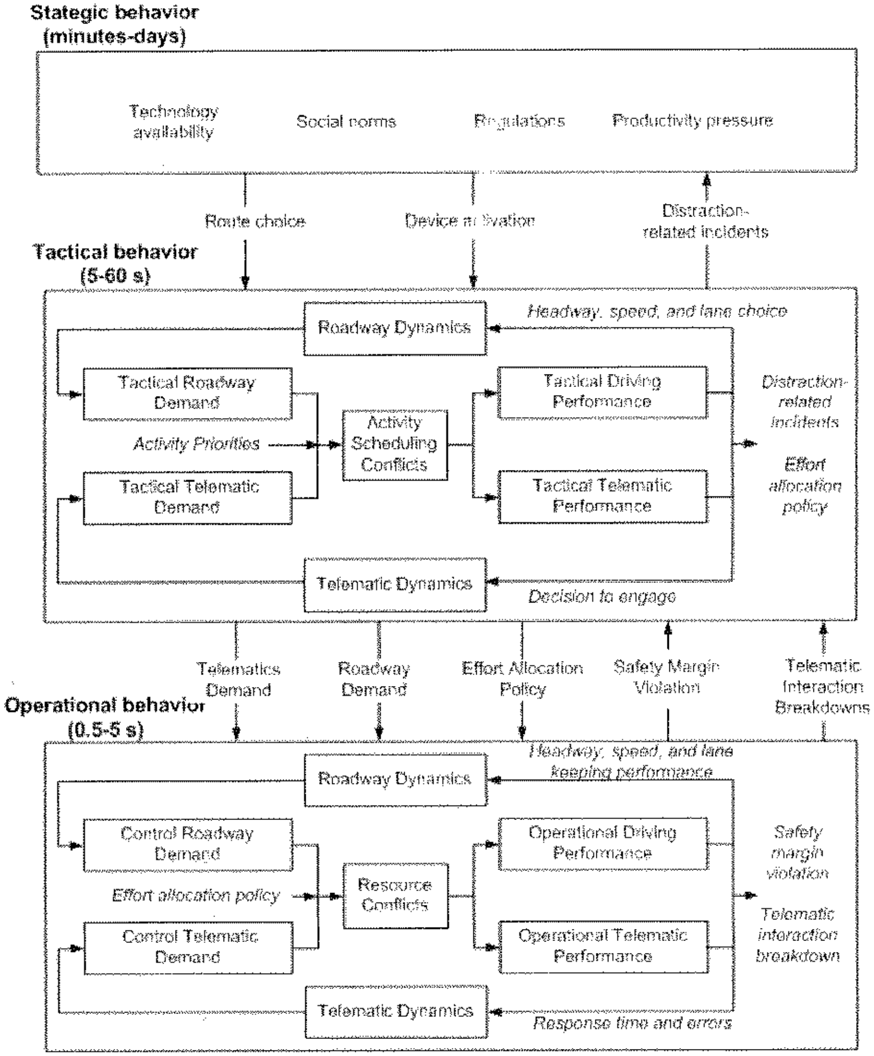

Figure 4.6. *Multilevel control that is shared between driving and other in-vehicle tasks (Lee & Strayer, 2004).*

Figure 4.6 shows three levels of control in driving and interacting with a telematics device such as a GPS-based navigation system or a cell phone. The top of Figure 4.6

occur at a very molar level with a time scale of minutes to days. Tactical behavior describes driving and telematic activities at a finer level, with a time scale of 5–60 seconds. At the bottom of the figure, operational behavior describes microlevel activity with a time scale of 0.5–5 seconds. Each of these levels provides a different description of how the characteristics of new technology interact with the driver to influence distraction-related safety problems.

The figure captures several critical elements that govern driving safety. First, it shows that failures of control at any of several levels can compromise driving safety. Second, behavior at the higher levels imposes performance requirements on the lower levels. Third, it shows that the parallel demands of driving and nondriving tasks compete for drivers' attention. Finally, it demonstrates that these demands evolve and that drivers adapt to these demands with time constants ranging from seconds to days. This adaptation means that drivers can often compensate for limits at one level by adapting at another. According to this representation, driving safety is highly dependent on how the higher levels set goals for the lower levels and how these goals are adjusted based on feedback from the lower levels.

Figure 4.6 also shows how cell phones can affect driving safety at several levels. The top of the figure lists factors that might lead drivers to bring a cell phone into the car. At the strategic level, societal norms and regulations might discourage drivers from using a cell phone in the car, but hands-free technology and productivity pressures may encourage them to do so. At the tactical level, the immediate roadway demands might influence the decision to answer the phone, whereas the perceived demands of a conversation might lead drivers to adopt longer headways or slower speeds. At the operational level, the cognitive demands of the conversation influence headway, speed, and lane-keeping performance.

Speeding and drivers' responses to crashes also demonstrate how the multilevel structure explains driving safety. Those who tend to speed also tend to view speeding as less consequential and to place a higher value on punctuality. This suggests that strategic concerns regarding the perceived utility of speeding influence speed selection (Adams-Guppy & Guppy, 1995). Immediate feedback associated with strategic driving decisions, such as being late for an appointment, outweighs the less salient feedback regarding the safety consequences of speeding. Remarkably, even after experiencing a severe crash, drivers often fail to alter their behavior. Drivers who survive a fatal crash adjust their driving only for a short period and only in situations similar to those that resulted in the crash (Rajalin & Summala, 1997). Frequency of feedback outweighs the dramatic but rare feedback associated with a crash. Inadequate anticipation of the effects of strategic and tactical decisions on operational behavior and poor feedback regarding choices at strategic and tactical levels of control represent critical contributors to crashes.

Beginning with Gibson and Crooks (1938), three general models of the driving process have had a particularly long-standing influence on driving safety research: field theory, sampling theory, and control theory. Each of these descriptions helps explain why drivers crash and also why drivers are remarkably adept at avoiding crashes most of the time:

- Drivers are not passive elements of the transportation system; they actively adapt to changes in roadway and vehicle technology.
- The appropriate unit of analysis in assessing driving safety is often not the driver but the driver-vehicle and driver-vehicle-environment combinations.
- Driving does not require complete attention, so drivers often divide their attention between the roadway and nondriving tasks. Unexpected events can make such intermittent sampling deadly.
- A multilevel description of driving that includes strategic, tactical, and operational levels suggests that many crashes reflect failures in the feedback mechanisms within and across levels. Drivers crash because they do not always see how their behavior compromises driving safety.

- Choices at the strategic and tactical levels of driving can lead to situations that exceed driver capacity at the operational level.

DRIVER CHARACTERISTICS

Crashes result often from a mismatch between drivers' perceptual and cognitive characteristics and the demands of the roadway environment. These characteristics influence the operational level of driving, but in many cases, drivers can adapt at the level of tactical and strategic behavior to mitigate the effect of these characteristics. In this section I describe some of the more salient driver characteristics that influence driving safety and examine the situations in which drivers successfully and unsuccessfully adapt to these limits. A fundamental challenge is to understand under what conditions and to what extent driver characteristics affect driving safety.

Vision and Perceptual Cues in Driving

Driving is highly dependent on visual perception, and one might expect measures of visual performance to predict safety. Although the contribution of visual information, relative to haptic and auditory cues, may be impossible to quantify precisely, vision is central to the driving task (Peacock & Karwowski, 1993; Sivak, 1996). One simulator study confirmed the primacy of vision in driving by dissociating the visual cues regarding roadway curvature from the centripetal forces. This study showed that drivers' head tilt strongly correlates with visual cues but not with centripetal forces, which is consistent with the primacy of vision (Zikovitz & Harris, 1999).

Paradoxically, measures of visual performance, such as acuity and binocular vision, are not strongly related to crash risk. In controlled experiments, visual acuity has been linked to impaired sign reading and hazard detection but has little effect on many driver maneuvers (Higgins, Wood, & Tait, 1998; Wood, 2002). Recent reviews confirm these findings, showing that visual acuity and color vision deficiencies have only weak links to crash involvement (Owsley & McGwin, 1999).

Likewise, even though visual performance begins to decline in relatively young adults, crash rates are lower for this group than for younger drivers with superior visual performance (Charman, 1997). Several large sample studies have shown statistically significant relationships between visual performance and driving, but no test or combination of vision tests can identify safe and unsafe drivers (Charman). One explanation for this paradox is that drivers compensate as they age. Older drivers recognize blurred text signs more effectively than younger drivers and are able to recognize novel signs more easily, suggesting that older drivers develop a general skill in accommodating blur (Kline, Buck, Sell, Bolan, & Dewar, 1999). Acuity is a stronger predictor of sign recognition for younger compared with older drivers (Kline et al.). Beyond gross visual impairments, visual performance has a surprisingly weak effect on driving safety (Olson & Farber, 2003).

Visual acuity declines dramatically as distance from the fovea increases and as light levels decrease. Drivers' 2° region of high visual acuity corresponds to the area subtended by the width of a car at approximately 140 feet (Olson & Farber, 2003). Even within this limited area of high-resolution vision, several perceptual thresholds severely limit drivers' ability to perceive other vehicles. Drivers cannot perceive acceleration directly, and they perceive speed poorly. Only when the relative velocity of the lead vehicle is such that its angular velocity surpasses 0.003 rad/s are drivers able to give reasonable estimates of the time to collision with a lead vehicle (Hoffmann & Mortimer, 1994). As a result, they often use information regarding whether vehicles are approaching or receding but often do not use relative velocity information effectively.

Adaptation of looming detectors that signal motion also compromise drivers' ability to estimate time headway during overtaking maneuvers and lead to risky passing maneuvers. Drivers made riskier decisions after they had been driving at a high speed compared with when they had watched a static picture or had adapted to contraction by driving backward (Gray & Regan, 2000). Owing to these limits, drivers in overtaking situations are not able to assess the speed of oncoming vehicles because the angular velocity is typically below the threshold at the time the overtaking maneuver is initiated. Limits of visual perception force drivers to rely on expected or typical speed.

Visual acuity is further diminished at night. Poor visual performance at night is one reason the rate of fatal crashes is three times that during the daytime (Owens & Sivak, 1996). One important contribution to this problem is glare. Even a small glare source can undermine a driver's ability to detect pedestrians, with older drivers being particularly vulnerable (Theeuwes, Alferdinck, & Perel, 2002). Even the mild opacity of the eye's lens that develops with age can dramatically reduce dynamic visual acuity (Anderson & Holliday, 1995). Interestingly, subjective estimates of glare poorly predict driving performance (Theeuwes et al.). As a result, drivers may not recognize the degree to which glare impairs their performance. The selective degradation of focal vision, which provides a high-acuity view of the world, contributes to the risk of driving at night.

Focal and Ambient Vision

The structural differences in foveal and peripheral vision, associated with location in the eye, roughly correspond to the functional distinction of focal and ambient vision (Leibowitz & Owens, 1977; Sarno & Wickens, 1995; Summala, Nieminen, & Punto, 1996). Focal vision supports form perception and identification of objects, whereas ambient vision supports spatial orientation and can help guide focal attention (Braun & Julesz, 1998). In driving, focal vision supports hazard detection and identification, and ambient vision supports longitudinal and lateral vehicle control in experienced drivers (Leibowitz & Owens).

The selective degradation of driving performance according to the location of the in-vehicle distraction and the type of driving task reflects the interaction of focal and ambient vision. In-vehicle tasks disrupted novice drivers even when the tasks required attention to a display positioned near the speedometer. The same tasks disrupted experienced drivers only when the display was located at the mid-console. These results suggest that experienced drivers can use ambient vision for lateral control, but inexperienced drivers cannot (Summala, Nieminen, et al., 1996).

In contrast, driving experience did not influence detection of lead vehicle braking events, which depend on focal vision. Both experienced and novice drivers demonstrated substantial impairment in detecting brake lights when looking in the direction of the speedometer and completely failed to detect such lights when looking at the mid-console (Summala, Lamble, & Laakso, 1998). Interactions with in-vehicle devices selectively degrade driving performance such that event detection, which depends on focal vision, degrades more dramatically than lane keeping, which depends on ambient vision. The ability to rely on ambient vision for lane keeping may mislead drivers regarding their ability to detect hazardous events. Further, feedback from successful lane-keeping performance may lead drivers to overestimate their ability to detect hazardous events when interacting with an in-vehicle device.

Selective degradation of focal vision has a similar effect on drivers at night (Leibowitz & Owens, 1977). Ambient vision is relatively unaffected by low illumination, whereas the acuity of focal vision declines dramatically. Because focal vision is impaired but ambient vision is not, drivers can maintain lane position but might not detect hazards. Substantial research suggests that drivers overestimate their ability at night because they receive little feedback regarding degraded visual detection and recognition ability but receive consistent and regular feedback regarding their unimpaired visual guidance ability (Leibowitz, Owens, & Tyrrell, 1998; Owens & Tyrrell, 1999). Poor feedback causes drivers to overestimate their ability and consequently to fail to adapt to changed illumination levels.

Visual Attention

The primacy of vision in driving, together with the dramatic decline of visual acuity as a function of the distance from the fovea, makes visual attention critical for driving. The limited span of focal vision forces drivers to scan the environment with multiple discrete fixations to maintain awareness of the overall driving scene. These fixations occur at a rate of approximately two fixations per second and so place a substantial constraint on how fast and to what degree drivers can scan the roadway environment (Moray, 1993). Such limits help explain why as many as 80% of intersection crashes result from one driver's failure to detect the other (M. Langham, Hole, Edwards, & O'Neil, 2002).

A complex interplay of features of the driving environment and driver expectations guides visual attention (Theeuwes, 1994). Features of the environment, such as abrupt onsets, guide attention in an exogenous or bottom-up manner. In contrast, driver expectations, such as learned associations between events on the road, guide attention in an endogenous or top-down manner. Breakdowns of the mechanisms that guide attention explain driving performance more effectively than do simple measures of visual acuity.

Substantial research shows that attentional impairments undermine driving safety, and tests of visual attention and speed of processing show substantial promise for identifying at-risk drivers (Ball, 1997; Owsley & McGwin, 1999; Roenker, Cissell, Ball, Wadley, & Edwards, 2003). Compared with the weak relationship between visual acuity and driving performance, a combination of motion sensitivity, useful field of view, contrast sensitivity, and dynamic acuity predicted 50% of drivers' overall test track driving performance (Wood, 2002).

Visual attention also helps explain the driving performance of inexperienced drivers. Inexperienced drivers make longer fixations and they scan smaller areas of the visual scene compared with experienced drivers (Mourant & Rockwell, 1972). Likewise, the longer fixation durations for novices in high-demand situations suggest they are more susceptible to attentional capture (Crundall & Underwood, 1998). With experience, their scanning adjusts to reflect the spatial-temporal characteristics of hazardous situations (Brown & Groeger, 1988).

As an example, drivers' scanning becomes more sensitive with experience to road type (Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003). Likewise, experienced police officers viewing high-speed pursuit videos have a greater sampling rate and spread of attention; in contrast, the attention to peripheral regions is less for inexperienced drivers compared with more experienced drivers who attend to hazardous locations with quick intense bursts of fixations (Crundall, Chapman, Phelps, & Underwood, 2003). Crash data support these on-road and simulator experiments and show that many young drivers crash as a result of failures of attention and visual search (McKnight & McKnight, 2003) and that many older drivers crash in attention-demanding situations, such as at intersections (McGwin & Brown, 1999; Preusser, Williams, et al., 1998).

The importance of visual attention in guiding drivers' limited visual capacity to scan the roadway environment also explains how cognitively demanding tasks that do not explicitly require visual attention, such as hands-free cell phone conversations, can degrade driving performance. A visual-manual task that involved entering a series of three-digit numbers using a keypad and a purely cognitive task that involved mental arithmetic both slowed driver response time to the deceleration of a lead vehicle by approximately 500 ms (Lamble, Kauranen, Laakso, & Summala, 1999). Similarly, a voice-based interaction with an e-mail system extended the reaction time of drivers to a braking lead vehicle by more than 300 ms (Lee, Caven, Haake, & Brown, 2001).

Several on-road (Recarte & Nunes, 2000, 2003; Sodhi, Reimer, & Llamazares, 2002), simulator (Strayer, Drews, & Johnston, 2003), and scene perception (McCarley et al., 2004) studies have shown that cognitive load influences visual attention and assimilation of roadway information. Both verbal tasks and spatial imagery tasks influenced the distribution of eye movements; the effect of spatial imagery tasks was particularly significant (Recarte & Nunes, 2000). Verbal production tasks influenced eye movements more than did listening, and verbal-spatial distinctions had less effect than the difference between production and perception (Recarte & Nunes, 2003). The general finding from these studies is that cognitive load can undermine drivers' ability to distribute visual attention effectively.

Attention, Expectations, and Hazard Response

Just as top-down expectations influence the distribution of visual attention to the roadway, these expectations also have a profound effect on driver response to potential hazards. Expectation plays an important role in the time it takes drivers to react to objects. Brake reaction time includes the time to detect a threat, release the accelerator, and move from the accelerator to the brake. On-road measurements of brake reaction time can range from 1.0 to 2.0 s for the average driver, with a mean of around 1.5 s (Green, 2000; Sohn & Stepleman, 1998).

It is important to note that the 1.5-s value is a mean, and driver characteristics and the driving situation can dramatically affect the time taken to react. For example, drivers respond to unexpected events relatively slowly but respond to severe situations more quickly (Summala, 2000). In the specific situation of a driver who is 10 m behind another vehicle and unaware that the lead vehicle is going to brake, the 85th percentile estimate of reaction time is 1.92 s and the 99th percentile estimate is 2.52 s (Sohn & Stepleman, 1998). In contrast, when the roadway situation and behavior of preceding vehicles lead drivers to expect a braking event, even a negative reaction time can result. As an example, drivers increased their headway and responded more quickly when situational cues made it possible to anticipate the deceleration of the lead vehicle (van der Hulst, Meijman, & Rothengatter, 1999).

Expectations affect the detection of hazards as well as response time. A common failing of drivers is looked-but-failed-to-see errors, in which drivers gaze toward a hazard but fail to perceive it. These errors are particularly prevalent with experienced and older drivers (Herslund & Jorgensen, 2003). Some looked-but-failed-to-see crashes reflect the influence of expectations on the perceptual process. This effect has been implicated in crashes in which drivers fail to detect emergency vehicles along the side of the freeway.

Experienced drivers viewing films of travel on a freeway were slower than less experienced drivers to respond to a highly conspicuous police vehicle when it was parked in line with the traffic (M. Langham et al., 2002). Experienced drivers expect vehicles in parallel with the traffic stream to be moving. When the emergency vehicle was parked in line, experienced drivers took 4.76 s to respond, whereas inexperienced drivers took only 4.5 s. In contrast, vehicles parked diagonally were more quickly detected by experienced drivers (3.12 s) compared with inexperienced drivers, who took 1.44 s longer. Cognitive load increased reaction time by 0.72 s for the diagonally parked scenario but by 1.41 s for the in-line one, indicating that the role of expectations becomes more dominant when cognitive capabilities are stretched (M. Langham et al., 2002).

Expectations play a similar role in motorcycle conspicuity. Motorcycles using headlights during the day are more easily detected, particularly at long distances; however, repeated exposure to motorcycles using headlights makes drivers more likely to fail to detect those that are not using headlights. This effect persists even when only 60% of the motorcycles use headlights (Hole & Tyrrell, 1995).

Expectations interact with the visual and functional context. The likelihood of detecting pedestrians or bicyclists depends on visual contrast and clutter, expectations, and cognitive load (M. P. Langham & Moberly, 2003). Expectations and impoverished cues cause many drivers to fail to detect pedestrians until after the drivers hit them (M. P. Langham & Moberly, 2003). Similarly, in a study of bicycle-car collisions in Finland, drivers failed to respond in any way in 61% of crashes (Rasanen & Summala, 1998). A common crash scenario involves drivers making a right turn at an intersection with a bicycle on their right side traveling straight. Only 11% of drivers noticed the cyclist before the crash (Rasanen & Summala). Video cameras used to observe drivers scanning an intersection showed that drivers tend to scan the left side of an intersection when turning right and neglect the bicycles in the bike lane on the right. Frequently, whether drivers notice a cyclist depends on whether another vehicle is nearby (Herslund & Jorgensen, 2003). Drivers adopt scanning strategies that focus their attention on the expected and salient risks, but these strategies may also neglect less obvious dangers (Summala, Pasanen, Rasanen, & Sievanen, 1996).

Behavior and Performance

Driver performance refers to the perceptual, cognitive, and motor limits that constrain how drivers can respond to roadway demands. Failures associated with driver performance reflect breakdowns at the operational level of Figure 4.6. In contrast, driver behavior refers to the choices drivers make at the tactical or strategic level. Behavior reflects the attitudes, goals, and priorities of drivers. Because strategic and tactical decisions often define the roadway demands confronting the driver at the operational level, factors that affect behavior may have a greater influence on driving safety.

For example, most drivers can maintain their speed within the posted speed limits; however, severe crashes often result when drivers choose to exceed the speed limit (Reason, Manstead, Stradling, Baxter, & Campbell, 1990). Also, males tend to have slightly shorter reaction times compared with females but crash more frequently; in other words, they perform better but behave worse (Evans, 2004). Driving safety depends on a complex interplay between the driver characteristics that influence performance and the feedback drivers receive that can influence behavior.

Drivers' perceptual and cognitive characteristics have a strong effect on driving safety, but a driver's ability to adapt complicates the relationship between these characteristics and roadway safety. The multilevel adaptation process diminishes the effect of some factors, such as visual acuity, and accentuates the effect of others, as with the overconfidence engendered by ambient vision at night. Considering how driver characteristics influence driving safety leads to the following conclusions:

- Visual perception plays a critical role in driving, but, paradoxically, simple measures of visual acuity do not predict driving safety.
- Selective degradation of ambient and focal vision can give drivers unwarranted confidence when driving at night and while looking away from the road, making them less able to adapt to these situations.
- Extremely limited foveal vision makes visual attention a critical factor in driving safety, and purely cognitive demands, such as conversations using hands-free cell phones, can degrade visual attention.
- Expectations have a profound influence on where drivers look, what they see, and how quickly they respond. Failure to adapt expectations to the situation undermines driving safety.
- Driver characteristics govern driving performance, but the interaction of these characteristics with driving behavior may have a more profound effect on driving safety.
- Driver characteristics influence behavior and performance; however, drivers are not a homogeneous population. There are substantial differences between drivers and in individual drivers over time, a topic addressed in the following section.

DRIVER TYPES AND IMPAIRMENTS

Research describing driver characteristics often assumes that drivers form a homogeneous population whose characteristics do not change over time. The reality is more complex. Driver capabilities change, even over the course of a day, varying according to alertness, which is governed in part by circadian rhythms. Drivers also change as they age and develop greater degrees of expertise. The dramatic overrepresentation of younger and older drivers in crash statistics demonstrates the power of these trends. Similarly, drivers differ in their tendency to engage in dangerous driving behaviors. Because of these differences, some drivers may be more likely to crash. A critical issue concerns the degree to which driver types and impairments contribute to crashes.

Individual Differences Affecting Driver Behavior

Some of the earliest research on driving suggested that "accident-prone" drivers play an important role in driving safety (Lauer, 1960). Substantial evidence over the last 15 years suggests that stable attitudes and behavioral differences do influence crash involvement (Parker, Manstead, Stradling, Reason, & Baxter, 1992). The Driver Behavior Questionnaire (DBQ) has been used in many studies, and consistent results indicate that it is capable of identifying the types of drivers who are disproportionately likely to be involved in crashes.

The DBQ catalogues the past behavior of a driver. Several large surveys and associated factor analyses of the results reveal a similar pattern. Such analyses have repeatedly shown a history of three principal factors that influence crash risk: lapses or absent-minded behavior, errors caused by misjudgment of danger or failures of observation, and violations or deliberate neglect of the conventions of safe driving (Blockey & Hartley, 1995; Parker, Reason, Manstead, & Stradling, 1995).

The distribution of errors and violations depends on gender and age. Young drivers and males tend to commit more violations compared with older drivers and females. Drivers with previous speeding convictions report more violations (Blockey & Hartley, 1995), and only violations predict crash liability (Parker, Reason, et al., 1995). Drivers' actual histories of traffic violations, such as the self-report data from the DBQ, have shown similar results. Drivers responsible for fatal crashes tend to violate traffic regulations more than other drivers, and those involved in fatal run-off-road crashes tend to have had the most violations (Rajalin, 1994).

Consistent with these results, an integrative review of workplace accidents found that individuals who commit violations, the tendency toward which behavior depends on sociopsychological factors, pose a greater accident risk compared with individuals who commit errors, the tendency toward which behavior depends on cognitive limits (Lawton & Parker, 1998).

A tendency to commit violations, as measured by the DBQ, is associated with a higher frequency of both active and passive crashes—crashing into someone and being crashed into. However, violations are also strongly associated with active loss of control and passive right-of-way crashes (Parker, West, et al., 1995). As an example, older drivers tend to crash more frequently in intersections than others, but observations of intersection negotiation by young and older drivers showed that situations in which the older driver is turning and the younger driver is proceeding straight result in the smallest safety margins (Keskinen et al., 1998). One explanation is that the younger drivers violate speed limits and so undermine drivers' top-down estimates of safety margins that depend on assumptions regarding the speed of the oncoming vehicles.

Other measures of individual differences have shown an association with driving behavior. An instrumented vehicle study showed that Type A personality traits were linked with higher speeds and shorter following distances (Boyce & Geller, 2002). A similar pattern of aggressive driving has been observed in several field studies. These studies show that close-following drivers commit more violations and crash more frequently. Close-following drivers accumulated twice as many traffic offenses as control drivers (Rajalin et al., 1997). Risk-taking drivers, as defined by the reciprocal of time headway, tended not to use seat belts, had more accidents and violations, and tended to be young and male (Evans & Wasielewski, 1983).

Consistent with this association of behaviors, drivers who used a cell phone while driving were also less likely to wear seat belts (Eby & Vivoda, 2003). Drivers observed not to wear seat belts had 35% more accidents and 69% more convictions in a previous four-year period compared with those who wore seat belts (Hunter, Stewart, Stutts, & Rodgman, 1993). These results show that drivers who engage in one risky activity tend to engage in others, and that the combination of risky behaviors leads to higher crash and injury rates.

A literature review of 40 studies revealed a consistent positive relationship between sensation seeking, particularly Zuckerman's thrill- and adventure-seeking subscale, and risky driving behaviors (Jonah, 1997). The correlation ranges between .30 and .40, depending on the subscale and the risky behavior being predicted (e.g., speeding, convictions, or crashes). Specifically, a survey of college students' driving behavior showed that those students with a high level of sensation seeking were more likely not to wear seat belts and to drive aggressively. High-sensation-seeking drivers were also more likely to report that they would drive faster on highways and on wet roads if driving a vehicle with antilock brakes (Jonah, Thiessen, & Au-Yeung, 2001).

A survey of 198 drivers between the ages of 16 and 19 revealed five distinct types of drivers. High-risk driving behavior, such as speeding, driving-related aggression, and hostility characterize two of these driver types. A subsequent simulator study showed impaired attention management performance of these drivers in high-workload situations (Deery & Fildes, 1999). Overall, individual differences associated with risk taking have a strong effect on driver behavior and crash rates.

Substantial research suggests that young drivers take more risks than mature drivers. However, several studies also cast doubt on this assumption. Data collected from a broad range of drivers using the DBQ survey generated a similar four-factor solution for all groups. In addition, the groups showed little difference in aberrant driver behavior as a function of age. These data suggest that age and gender may play a minor role compared with stable individual differences (Rimmo, 2002).

Analysis of the driving records of 149 000 British Columbian novice drivers between the ages of 16 and 55 found no evidence that younger drivers were more risky compared with older novice drivers (Cooper, Pinili, & Chen, 1995). However, drivers 16 to 18 years old who were carrying passengers did show a disproportionate crash risk during their first year of driving. A similar study compared the crash and conviction rates of 28 500 Finnish novice drivers in age brackets of 18–20, 21–30, and 31–50 years. The results show that young novice drivers–particularly males–had a greater number of strategic and tactical errors and that females tended to have greater problems at the operational level of driving behavior (Laapotti et al., 2001).

Overall, research suggests that drivers differ in their tendency to take risks and that these differences influence driving safety. Substantial (but not universal) evidence suggests that young male drivers are particularly likely to drive in a risky manner.

Young Drivers

Crash statistics show that young drivers, young males in particular, represent a substantial threat to driving safety. The factors that contribute to this threat are difficult to isolate. Most studies confound experience, lifestyle, and age. Age and gender may contribute to risk-taking tendencies, whereas lifestyle may contribute to fatigue. Experience influences the ability to evaluate hazardous situations and to control the vehicle (Summala, 1996).

A narrative analysis of 2000 crashes involving 16- to-19-year-old drivers found that most crashes result from errors of attention, visual search, speed selection, hazard recognition, and emergency maneuvers (McKnight & McKnight, 2003). Others have found younger drivers to be overrepresented in crashes involving high speeds, curves, alcohol, fatigue, distraction, and passengers (Ferguson, 2003; Williams, 2003). Overall, the predominant risk factors for younger drivers are lack of skill and poor judgment (McGwin & Brown, 1999).

Driving demands a high degree of motor skill, finely tuned attention, and precise judgment of hazards. These skills develop at different rates and take years to fully mature (Shinar, Meir, & Ben-Shoham, 1998). As a result, the skill of young drivers changes substantially as they proceed from 10 to 1000 to 10 000 hours of driving. The first months of unsupervised driving are particularly dangerous. Sixteen-year-old drivers have a crash rate 10 times as large as that of adults but experience a two-thirds reduction in their crash rate within the first 500 miles (McKnight & McKnight, 2003).

Similarly, a month-by-month analysis of crash rates in young drivers showed a 41% decline in the first six months and a 60% decline after two years (Mayhew et al., 2003). More impressive, survey data show that the probability of a crash in the first month, 0.053, was more than twice that of each of the following 11 months, 0.025 (McCartt, Shabanova, & Leaf, 2003). This reduction in crash rates partially reflects the development of basic control skills associated with the operational level of driving. For example, such drivers have a greater proportion of fatalities from rollover loss-of-control accidents, suggesting basic driving skill deficiencies.

After the first year of driving, the risk for young drivers is still much greater than that for adults. Even though young drivers quickly develop the basic skills necessary to control a vehicle, it takes several years to acquire the more subtle safe-driving strategies (Evans, 1991). For example, one study showed that when interacting with a radio, cassette player, or cell phone, no experienced driver glanced away from the road for longer than 3 s, but 29% of the inexperienced drivers did (Wikman, Nieminen, & Summala, 1998). Although young drivers may master basic motor skills such as shifting gears, these skills may not be automatized until they have been practiced for several years. The attentional demands of these tasks diminish drivers' ability to attend to and manage other driving tasks, such as sign perception (Shinar et al., 1998).

Comparing verbal roadway reports from experienced and novice drivers showed that experienced drivers are better able to attend to the driving environment (e.g., to perceive road signs, other vehicles, and scenery) while performing a nondriving task. This may reflect novice drivers' need to attend to the operational aspects of driving; more experienced drivers, having developed automaticity in performing these tasks, can attend to the tactical considerations of driving while performing a nondriving task (Lansdown, 2002).

After the first year of driving, young drivers may have acquired the basic skills of driving but not the judgment and highly practiced skills needed for safe driving (Ferguson, 2003; Tränkle, Gelau, & Metker, 1990). Consistent with this assertion, drivers with learner's permits crash at a rate one-sixth that of more experienced but unsupervised novices (Mayhew et al., 2003).

Eye movement data show that visual search by inexperienced drivers is less effective than that by more experienced drivers. The results of a study of visual search behavior, as measured by fixation duration and horizontal and vertical distribution of gaze, showed that experienced drivers adapt their scanning behavior to reflect the demands of the roadway. In contrast, novice drivers' search strategies lack the flexibility needed to accommodate the changing visual demands associated with different roadways (Crundall & Underwood, 1998). Novice drivers are also less sensitive to how the situation should influence the use of mirrors (Underwood, Crundall, & Chapman, 2002). The response of novice drivers to risky situations in a driving simulator confirms these findings and shows that young drivers lack the risk awareness needed for them to make sound driving judgments (Fisher et al., 2002).

Driver interaction with passengers also indicates how the poor judgment of young drivers leads to crashes. Passengers generally have a protective effect on drivers; people tend to drive more safely when passengers are present. But the protective effect is reversed with younger drivers carrying passengers of the same age (Vollrath, Meilinger, & Kruger, 2002). Passengers are associated with more at-fault crashes for drivers under 24 years of age. The effect of passengers is neutral for those between 25 and 29 and is associated with fewer at-fault crashes for those older than 30 (Preusser, Ferguson, et al., 1998). The relative risk of death increases substantially when passengers accompany younger drivers, to the extent that driving with three or more passengers increases the probability of a fatal crash by a factor of three (Chen, Baker, Braver, & Li, 2000). The risk is particularly high for young drivers carrying two or more passengers at night (Preusser, Ferguson, et al., 1998). Overall, passengers of the same age substantially undermine the safety of young drivers (Williams, 2003).

Two complementary tendencies may lead to judgments resulting in younger drivers' risky behavior: Younger drivers tend to overestimate their ability, and they underestimate hazards. Drivers generally overestimate their abilities. In one study, half the drivers judged themselves to be among the safest 20%, and 88% believed themselves to be safer than the median driver (Svenson, 1981). Such overconfidence may be particularly dangerous for younger drivers, who may not perceive hazards and so may be doubly impaired in their ability to adapt their behavior to the situation.

Older Drivers

In contrast to the skill deficiencies and poor judgment of younger drivers, it is attentional and information-processing impairments that lead to a relatively high crash rate in older drivers (Ball & Owsley, 1991; Stutts, Stewart, & Martell, 1998). These impairments contribute to the overrepresentation of older drivers in intersection crashes. Older drivers, however, are also typically effective in adapting their driving to compensate for information-processing impairments (De Raedt & Ponjaert-Kristoffersen, 2000). These compensatory strategies make it somewhat difficult to predict crash risk from psychomotor tests alone.

Crash and fatality rates begin to rise after 55 years of age (Ball & Owsley, 1991). For drivers over the age of 80, the risk of collision is 4.98 times greater than for drivers between the ages of 40 and 49 (Bedard et al., 2002). Intersection, lane-change, and merging crashes also pose a particularly high risk for older drivers. Older drivers are overrepresented in intersection crashes because they fail to yield the right of way (Preusser, Ferguson, et al., 1998).

One explanation for the increase in crash risk with age is that increasing age leads to poorer perception, slower response times, and a more restricted field of attention (Ball, Owsley, Sloane, Roenker, & Bruni, 1993; Owsley et al., 1998). Wood and Troutbeck (1994) used goggles to simulate the effects of cataracts, field restriction, and monocular vision on driving performance on a test track. Simulated cataracts had the greatest effect on driving; the monocular condition, on the other hand, did not significantly affect performance. Although visual acuity and impairment from cataracts can undermine driving performance, visual attention impairments pose a greater threat to older drivers. Substantial evidence suggests that a decline in visual attention undermines driving safety. The scanning patterns associated with the visual search of older drivers differ substantially from those of middle-aged drivers. Older drivers scan smaller portions of the driving scene and revisit previously scanned parts more frequently than do younger drivers (Maltz & Shinar, 1999).

Although information-processing limits undermine the performance of older drivers, particularly in complex traffic situations, such drivers avoid many crashes on the strength of their judgment and ability to adapt (McGwin & Brown, 1999). Older drivers compensate for their impairments by driving more slowly and cautiously, or by avoiding certain driving environments such as freeways or bad weather (Waller, 1991). Considered in terms of the strategic, tactical, and operational elements of driving, older drivers are less capable at the operational level but can compensate with appropriate choices at the tactical and strategic levels, such as avoiding left turns or choosing not to drive at night (De Raedt & Ponjaert-Kristoffersen, 2000).

A Canadian survey of people over 80 years of age found that 37.5% drove a motor vehicle at least once a year. Those who do drive tend to be male and free of chronic disease. Nondrivers tend to live with extended family and to suffer from one or more chronic diseases (Chipman, Payne, & McDonough, 1998). Drivers with visual or attentional impairments tend to avoid driving more than do those without impairments. Similarly, drivers with more impairments avoided more types of driving situations (Ball et al., 1998). Generally, older drivers are able to drive safely by adapting to a variety of cognitive and physical impairments.

Progressive dementias are particularly problematic, for they undermine critical attentional capacities as well as drivers' awareness of their own abilities and consequently their ability to adapt (Parasuraman & Nestor, 1991). This combination may make such drivers particularly prone to crashes. The centrality of driving in many people's lives may also undermine the ability of older drivers to adapt and remain safe drivers. As a consequence, tests to assess whether to curtail driving privileges are needed. Unsafe driving incidents were found to be correlated ($r = .4–.5$) with perceptual, attentional, cognitive, and psychomotor tasks; the correlation was somewhat less for visual abilities ($r = .3$) such as visual acuity (McKnight & McKnight, 1999).

A set of visual performance measures including useful field of view (UFOV), motion sensitivity, and dynamic acuity accounted for 50% of the variance in driving performance on a test track of drivers in young, middle, and older age groups (Wood, 2002). A computer-based battery of 22 perceptual, cognitive, attentional, and motor tasks successfully differentiated between drivers who had a history of unsafe driving acts and those who did not (McKnight & McKnight, 1999). In contrast, a battery of five tests was found to be ineffective in predicting unsafe driving. Results found that those drivers who performed in the lowest 10% had a crash rate only 1.5 times larger than that of those who performed in the top 10% (Stutts et al., 1998).

Driving records may also be a useful tool in identifying unsafe drivers. Prior crashes are better predictors of subsequent crashes for older drivers than are prior convictions (Daigneault, Joly, & Frigon, 2002), compared with younger drivers. Similar to a history of previous crashes, other mishaps, such as a recent history of falls, are also associated with increased crash risk (Lyman, McGwin, & Sims, 2001; Sims, Owsley, Allman, Ball, & Smoot, 1998). These studies show that no single measure is likely to identify at-risk older drivers and that a battery of perceptual, cognitive, and motor tests in combination with drivers' medical and crash histories may be necessary.

Even as screening tests are refined, substantial uncertainty remains regarding whether drivers who fail to meet the test criteria should actually lose their driving privileges. Drivers who lose their licenses also lose their freedom. Gradually curtailing driving privileges or using training and technology to mitigate the effects of aging might be a more effective approach.

Recent evidence suggests that drivers can be trained to improve their attentional capacity. In particular, training in selective and divided attention tasks improved UFOV performance, which was in turn associated with fewer errors in subsequent simulator-based evaluations of driving performance (Roenker et al., 2003). New technology also shows promise; collision warning systems might be tailored to help mitigate age-related driving impairments.

Fatigue

Fatigue undermines driving safety, particularly for young drivers and truck drivers (Summala & Mikkola, 1994). By one estimate, almost 30% of young adults sleep fewer than 6.5 hours each weeknight (Bonnet & Arand, 1995). The precise contribution of fatigue to crash rates is very difficult to quantify; researchers attribute 2%–25% of crashes to fatigue (Brown, 1994) and over 50% for truck drivers (Bonnet & Arand, 1995). Fatigue-related car crashes are typified by dry roads, high speed limits, drivers who do not drive daily, highly educated drivers, and those with limited driving experience. Such crashes are most common for those aged 25 and younger, with the peak seen among 20-year-olds (Pack et al., 1995).

Fatigue-related crashes follow a clear circadian pattern and peak at 3:00 a.m. In addition, fatigue depends on the time on task, with a peak after 2–4 hours that is exceeded only after 12 hours on task (Folkard, 1997). The circadian pattern also depends on the age of the driver. Young drivers are at most risk between midnight and 6:00 a.m., and drivers older than 56 are more at risk during the late afternoon hours (Summala & Mikkola, 1994).

Interviews with 593 long-distance truck drivers revealed that 47.1% reported having fallen asleep during their career, and 25.4% reported having fallen asleep in the last year (McCartt, Rohrbaugh, Hammer, & Fuller, 2000). Some of the factors associated with the tendency of truck drivers to fall asleep while driving include long work hours, few hours off duty, poor quality of sleep, and symptoms of sleep disorders (McCartt et al., 2000). Likewise, fatigue stems largely from prolonged and irregular work hours rather than time spent driving (Brown, 1994). A survey of truck drivers in 17 countries found that fatigue-related problems were connected with time of day and shift rotations but were much more strongly associated with how much latitude drivers had in managing breaks and route scheduling (Adams-Guppy & Guppy, 2003).

The work demands that induce fatigue are widespread. A survey of truck drivers found that in the 24-hour period before the survey, 38% of the drivers had driven more than 14 hours; 20% had slept fewer than six hours before starting on their current journey (Arnold et al., 1997). Another study found that a sample of 20 truck drivers averaged 5.18 hours in bed and 4.78 hours of electrophysiologically verified sleep, compared with a self-reported ideal amount of sleep of 7.1 hours (Mitler, Miller, Lipsitz, Walsh, & Wylie, 1997). Interestingly, several drivers reported fatigue to be a problem for other drivers but did not feel it affected their own driving performance (Arnold et al., 1997). Like truck drivers, younger drivers are particularly at risk for fatigue because they commonly suffer from disrupted sleep patterns. Sleeping fewer than 6.5 hours a day can be disastrous for driving performance (Bonnet & Arand, 1995).

Obstructive sleep apnea and other causes of sleep-disordered breathing contribute to daytime sleepiness and crash risk. As an example, researchers in one study found that truck drivers with sleep-disordered breathing were 3.4 to 7.3 times more likely to have had multiple crashes, depending on the degree of sleep apnea (Young, Blustein, Finn, & Palta, 1997). Obesity, often associated with sleep apnea and complaints of daytime sleepiness, was associated with a twofold increase in crash risk when body mass index was greater than 30 (Stoohs, Guillerminault, Itoi, & Dement, 1994). Assuming that 1% of the adult population suffers from sleep apnea and that drivers with sleep apnea have a crash risk three times as large as that of unaffected drivers, as many as 38,800 crashes might be prevented if these drivers could be identified and treated (Findley, Unverzagt, & Suratt, 1988).

Fatigue may also be responsible for many crashes other than those in which the driver is judged to have fallen asleep, so the true cost of fatigue is difficult to estimate (McCartt et al., 2000). A simulator study of drivers deprived of sleep the previous night found safety-critical declines in lane-keeping performance that were similar to the performance declines of drivers with blood alcohol content of 0.07% (Fairclough & Graham, 1999).

Another driving simulator study compared the effects of alcohol and prolonged wakefulness. Twenty-four hours of sustained wakefulness undermined driving performance to a degree similar to that caused by a blood alcohol content of 0.10% (Dawson & Reid, 1997). Even prolonging wakefulness by as little as three hours can affect speed and lane-keeping performance in ways similar to alcohol impairment (Arnedt, Wilde, Munt, & Maclean, 2001). These performance decrements show that fatigue may contribute to crashes even when the driver does not actually fall asleep.

Alcohol

Perhaps the most influential impairment on driving safety is alcohol. Alcohol has contributed to approximately 40% of fatal highway accidents in the United States. In 2003 alone, there were 17 013 alcohol-related deaths (NCSA, 2004). The effects of alcohol on driving performance are well known: Drivers with a blood alcohol content (BAC) as low as 0.05% react more slowly, are poorer at tracking, are less effective at time-sharing, and show impaired information processing (Evans, 1991). Although motor control is not greatly impaired, levels as low as 0.03% affect attentional control and could contribute to crashes (Bestard, Rossello, Munar, & Quetgles, 2001).

Although alcohol directly contributes to crashes, alcohol impairment is also associated with a constellation of other factors related to crashes. For example, in a sample of 165 injured motorcycle drivers, 53.3% showed elevated blood alcohol levels. Among those with elevated BAC levels, there was a greater prevalence of previous violations other than for those without elevated BAC levels; these violations included speeding (74% vs. 58%) and reckless driving (68% vs. 44%; see Soderstrom, Dischinger, Ho, & Soderstrom, 1993). Similarly, a study investigating a sample of trauma patients revealed that people involved in alcohol-related crashes often have a tendency toward risk taking and a pattern of motor vehicle violations (Soderstrom et al., 2001). An analysis of 907 New Zealand drivers under the age of 21 showed that those who engaged in a high rate of drinking and driving had a risk of crashing 2.6 times larger than that of those who did not drink and drive (Horwood & Fergusson, 2000).

Introducing increasingly restrictive laws regarding permissible BAC levels generally reduces the incidence of alcohol-related crashes (Mann et al., 2001). However, safety programs appear to be only partly successful in limiting the number of drunk drivers and curtailing the risky behaviors often associated with such drivers. Drinking and driving and other risky behaviors may share a common tendency associated with risk taking that may be most effectively countered by changing the broad societal expectations that help govern acceptable driving behavior (Evans, 1991).

Distraction

Longer commute times, increased productivity pressures, and rapidly developing in-vehicle technology all encourage drivers to engage in multiple tasks while driving. The term *in-vehicle information systems* (IVIS) describes a broad array of devices that enable drivers to use driving time to do tasks they would otherwise perform at the office, such as making telephone calls, managing e-mail, receiving navigation information, and retrieving information. In the United States, drivers have seen a steady increase in commute time; a third of an average driver's 350 hours spent driving each year are devoted to commuting (Hu & Young, 1999). Reflecting these factors, the percentage of drivers who were talking on a cell phone at a typical moment during daylight hours has increased from 3% in 2000 to 8% in 2004 (Glassbrenner, 2005). Such trends may substantially increase the number of distraction-related crashes.

Between 13% and 50% of crashes are attributed to driver distraction or inattention (Stutts, Reinfurt, Staplin, & Rodgman, 2001; Sussman, Bishop, Madnick, & Walter, 1985; Wang, Knipling, & Goodman, 1996). By one estimate, distractions associated with cell phones contribute to 2,600 fatalities, 330,000 injuries, and a total societal cost of $43 billion (Cohen & Graham, 2003). The demands of cell phone conversations and their contribution to driver distraction are well documented. Cell phone use can cause marked changes in the visual inspection patterns of drivers, such as reduced inspection of the mirrors, roadway, and speedometer (Recarte & Nunes, 2000). Cell phone use slows response to driving events (Alm & Nilsson, 1994; Alm & Nilsson, 1995), degrades perceptual judgments (Brown, Tickner, & Simmonds, 1969), and undermines decision making (Cooper et al., 2003).

Hands-free cell phones may help to alleviate the physical demands on the driver, thus reducing driver distraction and increasing performance. However, hands-free cell phones may not reduce crash risk because conversation is still cognitively demanding (Redelmeier & Tibshirani, 1997; Strayer et al., 2003). In fact, hands-free cell phones may degrade driving performance more than hand-held cell phones if the intelligibility of the hands-free device is less than that of the hand-held device (Matthews, Legg, & Charlton, 2003) or if drivers use phones more frequently because they believe the hands-free phones to be risk free. Aside from cell phones, many other types of in-vehicle technology may also demand drivers' attention, and speech interaction with these devices can also impair driving performance (Lee et al., 2001).

Drivers' tendency to adapt their behavior to the technology and the driving situation poses a general challenge in assessing IVIS technology (Poysti et al., 2005). As an example, a well-designed device that reduces distraction associated with each interaction might actually undermine driving safety if it encourages drivers to use the device more frequently. This usability paradox occurs when increased ease of use reduces the distraction of any particular interaction but increases overall risk by encouraging drivers to use the device more frequently (Lee & Strayer, 2004).

Likewise, distraction-related behavior results from a dynamic closed-loop process at the three different levels of behavior shown in Figure 4.6. This makes evaluating the distraction potential of a device difficult, because the evaluation must consider not only the distraction posed by the interaction but also the effect of the design on driv-

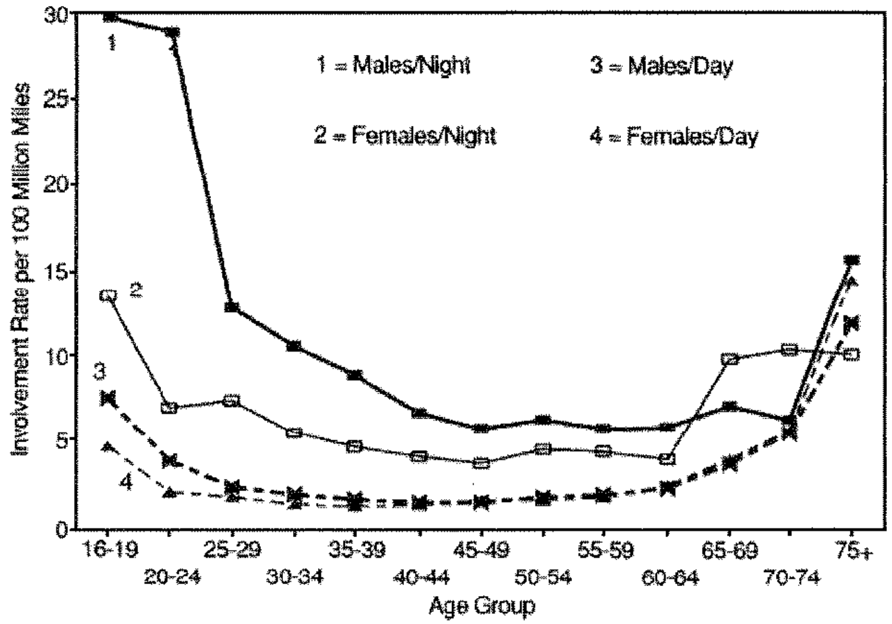

Figure 4.7. Interaction of age and time of day on crash involvement rate. Reprinted from Accident Analysis and Prevention, 27, *Massie, D. L. Campbell, K. L., & Williams, A. F., Traffic accident involvement rates by driver age and gender, 73–87, copyright (1995), with permission from Elsevier.*

extent that an evaluation does not facilitate this adaptive process, the results may not generalize to real driving. Forcing older drivers to engage in cell phone conversations in a simulator experiment may overestimate the true risk of cell phones for such drivers because they might normally make the strategic decision not to use them.

Finally, the most powerful factors governing distraction may be the most difficult to quantify and shape. In particular, the social norms governing acceptable risks—specifically, whether it is socially acceptable to use a cell phone while driving—may have the largest effect on driving safety. Subtle design modifications that reduce distraction at the operational level of behavior may have a much smaller effect on driving safety than changes in societal norms and laws that influence the strategic level and make using a device while driving taboo (Lee & Strayer, 2004).

Interaction of Factors

Risk-taking tendencies, fatigue, alcohol, age, and distraction can combine to degrade driving performance in a way that might not be predicted by each alone. This is particularly true with younger drivers. For example, young college students tend to have varied sleep patterns that can induce high levels of fatigue. They are also more likely to drive after drinking, and the combined effect of alcohol and fatigue can be particularly impairing. The presence of passengers can further compromise the situation by distracting the driver or inducing risky behavior. For a young person, driving with friends at night and after drinking is an extremely dangerous combination (Williams, 2003). Figure 4.7 shows the dramatic interaction of daylight and age on fatal crash rates. The effect of nighttime driving has the greatest effect on males; the relative risk for males rises from 2.4 during the day to 12.2 at night, whereas for females, it rises from 1.9 during the day to only 6.2 at night (Massie, 1995).

Individual differences regarding risk-taking behavior also interact to undermine safety. A tendency toward high speeds, neglect of stop lights, failure to use seat belts, and alcohol impairment may increase the probability of a fatal crash more than any of these factors alone. Similarly, distraction caused by a cell phone conversation may interact with low levels of alcohol to produce a deadly combination.

Substantial research clearly demonstrates that drivers are not a homogeneous group, and individual differences and impairments strongly contribute to crashes. Considering how driver types and impairments influence driving safety leads to the following conclusions:

- Risk-taking tendencies represent stable individual differences associated with risky driving behavior and crashes.
- Young drivers crash at very high rates owing to inadequate vehicle control skills and poor judgment, which may be compounded by overconfidence in their ability.
- Age-related declines in information-processing and attentional capabilities influence the crash rates of older drivers, but these declines are mediated by successful adaptation to many of these changes.
- The impairments of alcohol, fatigue, and distractions contribute to the majority of crashes and driving-related fatalities.
- Interactions between these driver types and impairments can be particularly deadly, such as the combination of a young driver under the influence of alcohol at night accompanied by several passengers.

HADDON'S MATRIX AS A GUIDE TO ENHANCING TRANSPORTATION SAFETY

Crashes result from complex interactions among many contributing factors. As a result, no single strategy will eliminate crashes. Instead, enhancing driving safety requires a systemic approach that considers drivers, vehicles, the roadway environment, and their interactions. Haddon's matrix addresses each of these considerations and shows how safety improvements can prevent crashes, minimize injury during crashes, and influence the treatment of injuries after the crash (Haddon, 1970); see Table 4.3. A critical consideration in applying the strategies in Table 4.3 is to recognize that the interactions between cells are critical and that focusing efforts only on the individual cells may neglect opportunities to improve safety (Noy, 1997). For example, young drivers are more likely to use and are more prone to be distracted by emerging in-vehicle technology, so graduated licensing programs should consider how to manage young drivers' use of in-vehicle technology.

Although each cell in Table 4.3 describes a potential strategy to enhance safety, the physics of the motor vehicle crash situation limit the benefit of the "crash" and

TABLE 4.3: Haddon's Matrix Showing Examples of How Driver, Vehicle, and Roadway Characteristics Contribute to Crash Avoidance, Crash Mitigation, and Postcrash Injury Treatment

	Drivers	*Vehicle*	*Environment*
Precrash	Training, graduated licensing, and traffic law enforcement	Collision warning systems Attentive IVIS Antilock brake system (ABS)	Roadway design Availability of public transport
Crash	Bracing behavior	Airbag Relative vehicle size	Barriers and lane separation
Postcrash	Emergency cell phone call	Automatic emergency call	Emergency vehicle response

"postcrash" rows. Over the last 40 years, substantial safety improvements have been made possible by significant improvements in the crashworthiness of vehicles, as well as in the roadway and medical infrastructure, so that what were once fatal crashes are now survivable. However, the physical limits on how much kinetic energy can be dissipated will soon be reached (Evans, 2004). For this reason, precrash mitigation strategies may be the most promising approach to enhancing driving safety.

Precrash Countermeasures

Considering the precrash strategies, a critical concern is the crash risk of young drivers. Though substantial effort is made to train younger drivers, there is little evidence that driver training programs actually serve to improve driver safety. In fact, they may actually undermine it if these programs allow drivers to be licensed at a younger age (Evans, 1991). Such training can also increase drivers' confidence in their abilities without enhancing their skill (Gregersen, 1996); however, training young drivers to judge risks holds promise (Fisher et al., 2002).

As a complement to training, raising the minimum driving age and introducing graduated licensing have both reduced crash rates. Graduated licensing, which restricts the driving privileges of young drivers during their first years of driving, is a particularly promising approach. Crash risk is low during the learner period (when drivers are accompanied by an adult) and particularly high immediately after licensure, at night, with passengers, and after consuming alcohol (McKnight & Peck, 2003). Graduated licensing restrictions reduce risky elements of driving for young drivers with the following restrictions: limiting nighttime driving, allowing driving only to and from school or work, permitting no young passengers, and driving only when accompanied by an adult (Williams, 2003).

Restricting nighttime driving and eliminating young passengers appear to be particularly successful (Lin & Fearn, 2003). These restrictions safely extend the training of the young driver for several years and reduce the crash rate for 16-year-old drivers by approximately 25% (McCartt, 2001; Shope & Molnar, 2003). Because young drivers disproportionately contribute to crash rates, structuring their first few years of driving could greatly reduce crash rates.

Enforcing existing traffic regulations could address many driving safety problems. The safety benefits of lower speed limits and adherence to the posted speed limit have been clearly established (Clarke, Ward, & Jones, 1999; Evans, 1991). Roadside signs that display drivers' speed relative to the posted speed have proven very effective. Such systems reduced the percentage of drivers who exceeded the speed limit by more than 10 mph from 15–20% to 2% and were particularly effective when placed in school zones (Casey & Lund, 1993).

Automatic speed management systems may offer the most effective tool for enforcing compliance with speed limits. These systems automatically limit the speed of the car to the posted limit by using GPS and electronic maps to identify the speed limit and then adjusting throttle and brakes to bring the car into compliance with the speed limit. Driver acceptance of such systems may be a substantial challenge (Varhelyi, 2002). Similarly, automated systems for issuing tickets for those who run red lights can promote compliance but are controversial (Lum & Wong, 2003).

Seat belt use, like many other driving safety practices, is greatly enhanced by regulatory enforcement—education alone is not sufficient, even though the relative risk of death for those wearing a seat belt compared with those who do not is approximately 0.4 (Cummings, Wells, & Rivara, 2003). Many studies have shown that primary seat belt laws (giving tickets for failure to wear a seat belt in the absence of any other offense) encourage higher levels of compliance than secondary laws, and that rigorous enforcement strongly influences compliance (Shults, Nichols, Dinh-Zarr, Sleet, & Elder, 2004; Williams & Wells, 2004).

Rigorous enforcement could substantially reduce alcohol-impaired driving; 100% compliance could save more than 13 000 lives and almost $40 billion each year in the United States (Dinh-Zarr et al., 2001; Shults et al., 2001). Similarly, 100% compliance with seat belt laws could save more than 9200 lives and over $25 billion. Eliminating speeding could save more than 12 000 lives and over $40 billion. Enforcement of traffic safety laws is an effective way to modify risky behavior, which is a large contributor to crashes and fatalities.

Emerging sensor, computing, and telecommunications technology has substantial potential to improve driving safety. Sensors can detect the distance and relative speed of the vehicle ahead and provide drivers with feedback regarding their headway. One study found that such feedback dramatically reduced drivers' tendency to adopt an unsafe time headway (less than 0.8 s) by approximately 25% (Shinar & Schechtman, 2002). A similar system that provided time headway through a visual display and an auditory alert reduced the amount of time drivers spent at headways below 1 s (Fairclough, May, & Carter, 1997). A comparison of visual and auditory displays of headway information showed that visual information is the most effective way to support headway maintenance, but auditory alerts may perform best for collision warnings

(Dingus, McGehee, & Hankey, 1997). Similarly, a combined auditory and visual warning for rear-end crash situations helped drivers respond more quickly and avoid crashes (Lee, McGehee, Brown, & Reyes, 2002).

Current vehicles and in-vehicle technology such as cell phones fail to consider driver or roadway state. New technology could create attentive IVIS, which would use sensors to monitor the driver and mitigate problems of distraction, fatigue, and alcohol (Brookhuis, De Waard, & Fairclough, 2003; Brookhuis & Dewaard, 1993; Hancock & Verwey, 1997). Monitoring driver, vehicle, and roadway states makes a range of mitigation strategies possible, such as filtering incoming cell phone calls, shifting the threshold for collision warnings to warn impaired drivers earlier, and alerting drivers to their impairments (Donmez, Boyle, & Lee, 2003). Such systems can prevent crashes by augmenting drivers' perception and attention in responding to the roadway environment.

Although promising, such technology may not perform as expected (Tenner, 1996). Poor understanding of antilock brake systems (ABS) capabilities can undermine their potential benefit (Mollenhauer, Dingus, Carney, Hankey, & Jahns, 1997). More important, drivers may adapt their driving to capitalize on the capability of ABS. Taxi drivers with ABS had significantly shorter time headways compared with taxis without ABS (Sagberg et al., 1997). Evans (2004) reviewed several studies that showed that rollover risk increased from 14% to 94% for vehicles equipped with ABS. Adaptation to safety measures has also been documented with crosswalks. Twice as many pedestrians were hit at marked crosswalks as at unmarked crosswalks. This does not reflect any particular feature of the marked crosswalks but, rather, an inappropriate adaptation on the part of pedestrians, who overestimate the protective benefit of the crosswalk (Herms, 1972). The design of any safety intervention must consider the tendency of drivers to adapt (Stetzer & Hofmann, 1996; Wilde, 1988).

The roadway infrastructure can also have a profound effect on driving safety. Roadway design affects speeding and the ability of drivers to anticipate potential hazards. A design philosophy known as *positive guidance* has led to the development of solutions that help drivers anticipate decision points, such as slowing for a curve or braking for a stop sign (Alexander & Lunenfeld, 1990). Positive guidance allows designers to work with the natural environment and sign placement to help drivers avoid sudden braking and unsafe speeds. Another successful example of roadway design enhancing safety is the 2 + 1 scheme for rural highways, in which a standard two-lane highway is augmented with a third lane that alternates as a passing lane for each direction of travel. Such roadways have resulted in a 22%–55% reduction in crashes where they have been implemented in Europe (Derr, 2003).

The roadway infrastructure also includes the availability and quality of public transport. Because travel by public transport is far safer than by private cars, safety could be substantially improved with greater participation in public transport.

Postcrash Countermeasures

Table 4.3 shows several examples of driver, vehicle, and roadway features that enhance postcrash response. These interventions are designed to help keep the driver alive after a crash. The most critical factor contributing to survival after a crash is the time it takes to get the driver to an emergency room. Cell phones make it possible for the driver to call for help easily (Redelmeier & Tibshirani, 1997), reducing the time emergency vehicles take to arrive on the scene. However, in severe crashes the driver may be disabled. For this reason, new systems automatically call for aid if the airbag is deployed.

The roadway and traffic infrastructure also plays an important role in the postcrash response. Traffic congestion might prevent emergency vehicles from reaching the driver in a timely manner, and appropriate emergency room resources may not be available. Navigation systems in ambulances that indicate low-congestion routes to the victim could also enhance postcrash response.

Overall, interventions to enhance driver safety can pay large dividends. A device that reduces a car's crash involvements by 5% over its life would have a societal economic value of $1420 for each vehicle in which it is installed (Wang, Knipling, & Blincoe, 1999). Similarly, education, licensing policies, or enforcement of regulations that could decrease crash involvements by 10% over the lifetime of the driver would have an economic value of $8160 for each young driver (Wang, Knipling, & Blincoe).

CONCLUSION: RISK MANAGEMENT AND DRIVING SAFETY

The factors that contribute to crashes are complex and diverse. Crashes can be considered from the perspectives of crash types, the driving process, driver characteristics, individual differences, and impairments. Each of these perspectives provides a complementary and overlapping account for why crashes occur. An outcome of this description is the realization that no single factor accounts for crashes and that any intervention to improve safety can have unexpected consequences. The major contributor to the complexity of driving safety is the multifaceted and adaptive nature of drivers, which has been the primary focus of this review. In addition, driving safety depends on the social and organizational factors that influence drivers and the infrastructure that supports driving. Understanding why so many people die on the roadways each year depends on more than the interactions between drivers, their vehicle, and the roadway environment.

Figure 4.8 shows a framework of risk management developed for complex sociotechnical systems that places driving in the context of social, organizational, and cultural factors that contribute to driving safety (Rasmussen, 1997). Like the multilevel control framework that described the strategic, tactical, and operational activities of driving at the start of this chapter, Figure 4.8 describes driving safety as a multilevel control process. The two bottom levels correspond to the actual driving activity described in Figure 4.6. The upper levels highlight the social and organizational factors that influence driving safety. Just as interactions between levels and poor feedback lead to breakdowns in driving performance, problems emerge at the societal level in managing driving safety.

An important challenge in addressing driving safety is the multidisciplinary perspective required for a systematic solution. The left side of Figure 4.8 shows the range

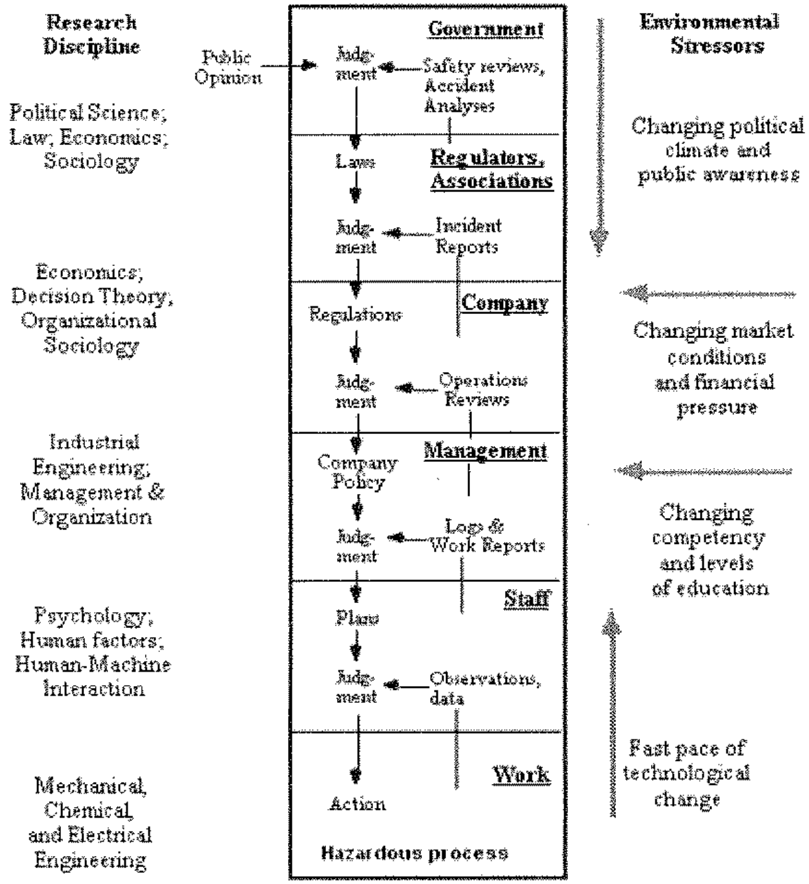

Figure 4.8. *Driving safety as a societal risk management challenge. Reprinted from* Safety Science, 27, *Rasmussen, J., Risk management in a dynamic society, 183-213, copyright (1997), with permission from Elsevier.*

of disciplines that may be involved. As an example, the engineering expertise needed to develop ABS and collision warning systems is not sufficient to ensure that such systems actually enhance driving safety (Deering & Viano, 1998). Effective deployment of these systems also depends on human factors expertise to craft an interface that drivers will understand and accept. Likewise, the most effective interventions may require a shift in societal values and acceptable costs and so require expertise in public policy. At the highest level, driving safety depends on political decisions and governmental priorities. The interactions between levels further exacerbate the multidisciplinary challenge. Not only are multiple disciplines needed, but the interactions between levels require close cooperation between groups that rarely interact, such as human factors specialists and public policy experts.

Figure 4.8 highlights another important challenge: control in the face of a diverse range of environmental stressors, shown on the right of the figure. These diverse stressors and the range of time scales present a substantial challenge. For example, the rate of information technology development is rapid, with major innovations occurring on a time scale of months. This conflicts with the much slower pace of innovation in the automotive industry. The pace of regulatory intervention has evolved to address the relatively slow pace of the traditional automotive industry. In addition, the information flow from traffic incidents and accidents upward to those making regulatory decisions is imperfect and delayed. The safety consequences of new information technology illustrate this problem. A distracting product might be used for years and contribute to the deaths of thousands of people before regulatory agencies identify the problem and are able to respond. By the time they respond, a new product with a different set of safety concerns may have replaced the original.

One approach to these challenges is to develop computational models that can anticipate the effects of the factors influencing driving safety and support feedforward control. Such models are needed at the lowest level of the process so that new designs can be rapidly adjusted in advance of more costly and time-consuming human-in-the-loop simulation and on-road tests. Computational models such as those based on the ACT-R cognitive architecture offer great promise in predicting the effect of distraction, at least at the operational level of driving behavior (Salvucci & Macuga, 2002). Several modeling efforts have begun to link the microlevel behavior of individual drivers with macrolevel traffic behavior (Kerner & Klenov, 2002; Kerner, 2002; Helbing, Hennecke, Shvetsov, & Treiber, 2002). Such models of driver performance and behavior may make it possible to extrapolate from controlled studies to estimate the overall benefits of safety interventions. Such models can enhance the feedback process and provide a tighter coupling between the upper and lower levels of Figure 4.8.

Recommendations for Enhancing Driving Safety

This review describes driving safety problems as breakdowns of a complex multilevel control process. For the individual, this process spans operational, tactical, and strategic levels of control. Beyond the individual, it spans everything from traffic behavior to regulatory policy and cultural norms. Considering the problem of driving safety in the context of this complex control process identifies two sets of interventions to improve driving safety.

Dangerous situations emerge when drivers' perception of risks diverges from the actual situation. Providing better feedback and guiding drivers' behavior where feedback is impoverished could greatly enhance safety.

1. Rigorous enforcement of strict laws regarding alcohol, seat belt use, and speeding.
2. Development of driver support systems that combine sensor data and attune drivers to the evolving roadway situation.
3. Development of driver support systems that help drivers moderate the flow of in-vehicle information systems according to the roadway demands.
4. Improvement of the feedback and guidance to at-risk populations such as old and young drivers through graduated licensing and in-vehicle systems that could monitor their progress.

Driving safety depends on more than interventions affecting individual drivers. Ultimately, major improvements in driving safety depend on broader considerations, such as the need to develop a deeper understanding of the fundamental mechanisms underlying driving safety and the development of social norms associated with a culture that values safety.

1. Development of computational models to support proactive technology evaluation.
2. Development of computational models to link microlevel descriptions of driver behavior to macrolevel outcomes of traffic flow in order to assess the benefits of safety interventions.
3. Support of basic research and training of researchers to address the complex human, technological, and social problems associated with driving safety.
4. Increased societal commitment to the value of human life relative to convenient and rapid transit.

The ultimate value of any one of these strategies is hard to assess, but the consequence of inaction is obvious.

ACKNOWLEDGMENTS

The comments of many people greatly enhanced this chapter. In particular, I thank Linda Boyle, Leonard Evans, Barry Kantowitz, Monica Lees, Teresa Lopes, Daniel McGehee, and Bobbie Seppelt. Ray Nickerson was particularly helpful in guiding the development of this chapter.

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CHAPTER 5

Improving Product Safety and Effectiveness in the Home

By Deborah A. Boehm-Davis

The Centers for Disease Control and Prevention report that accidents rated as the fifth leading cause of death in 2002. A large proportion of these accidents occur in and around the home. For 2003, the Consumer Product Safety Commission (CPSC) estimated that just under 11 million injuries were caused by children's nursery equipment; toys; sports and recreational equipment; home communication and entertainment; household containers; yard and garden equipment; home workshop equipment; home maintenance; general household appliances; heating, cooling, and ventilation equipment; home furnishings and fixtures; and home structures and construction materials. Even those products that are safe to use may not be designed to allow the user to be maximally effective when using those products. This chapter describes a framework that can provide a foundation for understanding the components that play a role in making products safe and effective, a process that can be used by designers to ensure a consideration of the components of the framework, and a discussion of the extent to which consumers select products based on these features. Difficulties in conducting research in this area are identified, as well as some directions for future work.

When my daughters reached an age where they woke up before me and started making their own breakfast, I decided it would be prudent to purchase a bagel slicer. Unfortunately, I did not take my users sufficiently into account. The first time one of my daughters used our new bagel slicer, she sliced her finger instead of the bagel.

My daughter was supposed to put the bagel into the slicer, insert the knife at the top of the holder with one hand, and then place her other hand over the top of the bagel and knife, squeezing the holder together while slicing downward (see Figure 5.1). Unfortunately, she didn't understand the order in which these operations had to be done. She placed her hand on the holder before placing the knife in position. As a result, the knife slashed her hand before it reached the bagel.

Most people think of their home as a safe haven—a place where they can get away and hide comfortably and safely from the dangerous world. The reality, however, is that many accidents happen in the home. In fact, the Centers for Disease Control and Prevention reported that accidents rated as the fifth leading cause of death in 2002 and that a large proportion of these accidents occurred in and around the home (Kochanek, Murphy, Anderson, & Scott, 2004).