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Preventing Emergency Vehicle Crashes: Status and Challenges of Human Factors Issues

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Objective: This study reports current status of knowledge and challenges associated with the emergency vehicle (police car, fire truck, and ambulance) crashes, with respect to the major contributing risk factors.

Background: Emergency vehicle crashes are a serious nationwide problem, causing injury and death to emergency responders and citizens. Understanding the underlying causes of these crashes is critical for establishing effective strategies for reducing the occurrence of similar incidents.

Method: We reviewed the broader literature associated with the contributing factors for emergency vehicle crashes: peer-reviewed journal papers; and reports, policies, and manuals published by government agencies, universities, and research institutes.

Results: Major risk factors for emergency vehicle crashes identified in this study were organized into four categories: driver, task, vehicle, and environmental factors. Also, current countermeasures and interventions to mitigate the hazards of emergency vehicle crashes were discussed, and new ideas for future studies were suggested.

Conclusion: Risk factors, control measures, and knowledge gaps relevant to emergency vehicle crashes were presented. Six research concepts are offered for the human factors community to address. Among the topics are emergency vehicle driver risky behavior carryover between emergency response and return from a call, distraction in emergency vehicle driving, in-vehicle driver assistance technologies, vehicle red light running, and pedestrian crash control.

Application: This information is helpful for emergency vehicle drivers, safety practitioners, public safety agencies, and research communities to mitigate crash risks. It also offers ideas for researchers to advance technologies and strategies to further emergency vehicle safety on the road.

Keywords: police vehicle, ambulance, fire truck, intersection, roadway design, driver assistance systems

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INTRODUCTION

The Problem of Emergency Vehicle Crashes

Motor vehicle crashes involving emergency vehicles, such as police cars, fire trucks, and ambulances, have been recognized as a serious problem nationwide (Savolainen, Dey, Ghosh, Karra, & Lamb, 2009). The National Highway Traffic Safety Administration (NHTSA; 2011) reported that 559 law enforcement officers (LEOs) were killed by vehicle crashes during the period of 2000 to 2008. This accounted for 53% of LEO work-related fatalities in this time period. Also, according to the U.S. Fire Administration (USFA), 179 firefighters died as the result of vehicle crashes from 2004 to 2013 (USFA, 2014b). Emergency medical service (EMS) technicians face a similar risk of death from emergency vehicle crashes. The National EMS Memorial Service reported that approximately 97 EMS technicians had been killed by ambulance collisions from 1993 to 2010 in the United States (Maguire, 2011). The traffic-related fatality rates of these occupations are particularly alarming; the rates for LEOs, firefighters, and EMS technicians were estimated to be 2.5 to 4.8 times higher than the national average among all occupations (Maguire, Hunting, Smith, & Levick, 2002). Moreover, the best available data showed that an average of 27,235 documented total crashes involved law enforcement vehicles each year and resulted in a total of 37,655 LEO injuries during the period 2004 to 2006 (USFA, 2014a). Also, in 2015, there were 16,600 fire apparatus and 700 firefighter privately owned vehicle collisions, resulting in 1,200 injuries to firefighters (Haynes & Molis, 2016). And in 2009, there were 1,579 ambulance crash injuries (Grant & Merrifield, 2011).

Aside from the fatality and injury risk to LEOs, firefighters, and EMS technicians, emergency vehicle crashes often have serious community implications. Emergency vehicle crashes may involve the civilian population and properties (NHTSA, 2011; Pirrallo & Swor, 1994). From 1979 through 2013, incidents involving law enforcement vehicles during police chases resulted in approximately 2,400 civilian fatalities (Frank, 2015). Also, from 1996 to 2012, there were 137 civilian fatalities and 228 civilian injuries resulting from fire service vehicle incidents and 64 civilian fatalities and 217 civilian injuries resulting from ambulance incidents (USFA, 2014a). Moreover, emergency vehicle crashes have incurred many lawsuits filed in the aftermath of crashes and cost millions of dollars every year due to loss of life, injuries, and property damage (Eckstein, 2004; Owens, 2016).

Currently, more than 900,000 sworn LEOs (National Law Enforcement Officers Memorial Fund, 2017), 1,134,400 career and volunteer firefighters (Haynes & Stein, 2016), and 826,000 licensed and credentialed EMS personnel (Federal Interagency Committee on Emergency Medical Services, 2012) serve in the United States. Most of these workers use emergency vehicles as part of their jobs. Strategies and actions for reducing emergency vehicle crashes are undoubtedly needed. A systematic review of risk factors, current control measures, and knowledge gaps relevant to emergency vehicle crashes may be useful for establishing effective strategies to reduce the occurrence of similar incidents and suggesting knowledge gap areas where further research is needed.

Emergency Vehicles and Emergency Driving

Emergency vehicles are designated and authorized to respond to an emergency that is defined as "a situation that poses an immediate risk to health, life, property, or environment" (Wikipedia, 2017). Three primary groups of emergency vehicles are recognized: police and law enforcement, fire and rescue, and medical. Approximately 410,000 police vehicles, 160,000 fire apparatus and supporting vehicles, and 48,000 ambulances are in use in the United States (Gaines & Weikersheimer, 2015; Haynes & Stein, 2016).

Depending on their function, emergency vehicles can have unique designs and specialized equipment. For example, many fire trucks are large and heavy, while police cars are often powerful and fast. Most emergency vehicles are also equipped with computers and radio communication equipment. Furthermore, emergency vehicles are often painted and marked for increased visibility and recognition and are equipped with lights and sirens to help negotiate traffic and minimize travel time (De Lorenzo & Eilers, 1991; Saunders & Heye, 1994).

When responding to an emergency call, emergency vehicle drivers are given the "code 3 running" option (Slattery & Silver, 2009; USFA, 2014a). A "code 3 running" is defined as the use of warning lights and sirens, and drivers may be permitted to exceed speed limits and cross against stop signs and red lights in order to minimize travel time (Central California Emergency Medical Services, 1983). However, the implementation of this policy varies, depending on affiliated agencies' standard operating procedures (SOPs) and variations in state traffic laws and regulations. Emergency response driving is also characterized by time pressure, stressful driving conditions, and multitasking activities. Driving under time pressure is frequently associated with speeding and potentially risky driving behavior. Mental and emotional stress may also cause unsafe vehicle operation, and multitasking activities may lead to distraction during driving.

The unique characteristics of different emergency vehicles and the emergency driving (ED) task may be associated with an increased risk of crashes. Analyzing and understanding the underlying risk factors will help develop effective crash prevention strategies.

Literature on the Risk Factors of Emergency Vehicle Crashes

Studies have attributed emergency vehicle crashes to a number of causative factors: driver workload and fatigue from long driving hours and irregular shifts (Abdelwanis, 2013), driver mental and physical stress resulting in decreased performance (Kahn, Pirrallo, & Kuhn, 2001), vehicle weight and mechanical malfunctions (USFA, 2002), lack of recognition of emergency vehicles by other drivers (Saunders & Heye, 1994), lack of training and qualifications for operating heavy vehicles (USFA, 2014a), complicated urban intersections (Retting, Williams, Preusser, & Weinstein, 1995), overconfidence in driving in favorable environmental conditions (Custalow & Gravitz, 2004; Pirrallo & Swor, 1994), risky driving (Savolainen et al., 2009), and high traffic volumes in urban areas (Ray & Kupas, 2007). These studies understandably have certain limitations. In each of these studies, the case number and conditions of emergency vehicle crashes studied were confined. Thus, the risk factors may not be well portrayed in a single report. A comprehensive search and synthetization of major risk factors associated with emergency vehicle driving and crashes is warranted for use in developing crash reduction strategies.

Association Between Emergency Vehicle Crashes and General Motor Vehicle Crashes

Due to public and social demand as well as a higher number of general motor vehicles than emergency vehicles in operation, much more information is available on general motor vehicle crashes than on emergency vehicle crashes. Some risk factors may be shared between emergency and general motor vehicle crashes, although emergency vehicle drivers have different driving behaviors due to "code 3 running," and some emergency vehicles have unique performance characteristics. Examples of the shared risk factors are intersection encounters (Kahn et al., 2001; Polders, Daniels, Hermans, Brijs, & Wets, 2015), drivers' experience (Becker, Zaloshnja, Levick, Li, & Miller, 2003; Retting, Ulmer, & Williams, 1999), drivers' distraction (Horberry, Anderson, Regan, Triggs, & Brown, 2006; Kaber, Liang, Zhang, Rogers, & Gangakhedkar, 2012), and geometrical road design and arrangement (Abdel-Aty & Wang, 2006; Tay & Rifaat, 2007). An analysis of risk factors associated with general motor vehicle crashes that may be relevant to emergency vehicle operation may provide further insight for emergency vehicle crash reduction as well as for comparisons between public motor driving and emergency vehicle driving.

Objective

The objective of this article was to report the status and challenges of human factors issues associated with emergency vehicle driving and crashes and their unique issues as compared to general vehicle operation, with respect to driver, task, vehicle, and environmental risk factors, based on the broad literature on transportation safety. Current countermeasures and interventions to mitigate the hazards of emergency vehicle crashes were discussed, and new ideas for future studies were suggested. The information serves as a foundation for readers at large to expand on in-depth reviews for each reported key issue in this article and to collaterally and strategically conduct research to reduce national emergency vehicle crashes.

METHODS

Systematic Review Framework

From a human factors perspective, any vehicle crash can be seen to result from control failures during interactions in the system of road users, vehicles, and the environment (Dewar & Olson, 2007). In the broader sense, these interactions may include (a) road users' personality traits and belief systems; their education and training; and their physical, mental, and emotional states; (b) vehicle design, maintenance, and operation, including safety features and systems; (c) the built and natural environment, including infrastructure, roads, and traffic control devices; and (d) climate conditions. These interactions are "regulated" through the development, implementation, and enforcement of traffic-related rules defined by regulations, standards, state laws, and policies. However, these rule-based control strategies may not always be effective due to various individual, organizational, and societal factors. The user-vehicle-environment interactions are also directly influenced by distinct emergency vehicle driving tasks that involve heavy secondary-task demands, such as operating warning devices, communicating with dispatchers, and monitoring potential threats (Figure 1). This study identified risk factors by synthesizing current knowledge on emergency vehicle crashes through a systematic review on human factors issues, using this frame structure. Based on the results, the article also identified control measures for current safety practices and unique challenges of emergency vehicle driving for future research development.

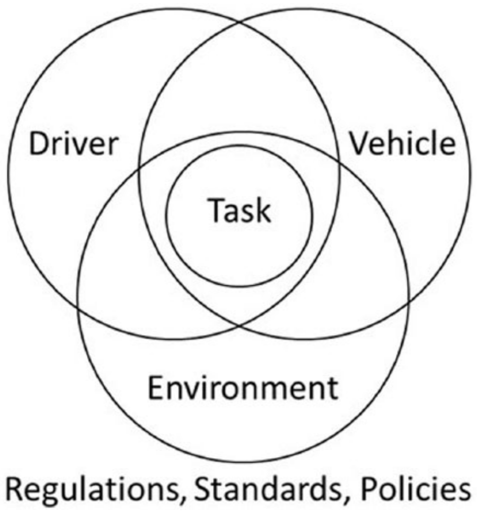

Figure 1. Framework: system of factors involved in emergency vehicle crashes.

Systematic Review Criteria

A list of papers on the topic of emergency vehicle crashes was obtained using literature search engines such as Google Scholar, ScienceDirect, the Centers for Disease Control and Prevention (CDC) Library Catalog, and transportation-related journals and injury data systems. The search was conducted using a series of keywords such as *police car, fire truck, ambulance, emergency vehicle, vehicle crashes*, and *intersections*. Aside from the peer-reviewed journal papers, the search also identified a number of related reports, articles, policies, and manuals published by government agencies, universities, and research institutes. The initial results revealed that the literature on emergency vehicle crashes is somewhat limited, and thus the search was extended to cover general motor vehicle crashes to identify additional contributing and potential risk factors that may also be associated with emergency vehicle crashes. The expansion also provided information for comparisons between emergency vehicle crashes and general motor vehicle crashes. The papers obtained in the initial search were screened using the following criteria: (a) a paper presented new data or comprehensive information from a selected group of studies on emergency vehicle crashes; (b) a paper addressed emergency vehicle crashes or the risk factors that may result in emergency vehicle crashes; (c) a paper accounted specifically for driving safety of police vehicles, fire trucks, or ambulances; and (d) the results of a paper could be associated with emergency vehicle driving or crashes. Only those papers based on substantial and scientific evidence were included in the review phase. The selected papers were fully reviewed, and attention was given to the following three themes: (a) findings about suspected risk factors for emergency vehicle crashes, (b) findings about science-based strategies and interventions for mitigating emergency vehicle crashes, and (c) research gaps about the prevention of emergency vehicle crashes. A total of 267 papers and documents were included in the final synthetizations for risk-factor identification. This article reports the most critical issues and covers 180 publications. Some subjects, such as effects of left-turn signal logic, sign-controlled intersections, and public awareness on emergency vehicle crashes, are not included due to space constraints. Of the 180 publications, 118 were peer-reviewed articles that covered laboratory experiment studies, laboratory simulations, and field experiments. Fifty-five publications were technical papers that covered authoritative guidelines, data-based technical notes, dissertations, books, and policy documents. Seven other publications were associated with national or state-based injury and fatality data systems and risk assessments. A few of the peer-reviewed articles and technical papers utilized a part of national injury and fatality data systems, such as Fatality Analysis Reporting System (FARS) and National Motor Vehicle Crash Causation Survey (NMVCCS). They were rolled in the categories of peer-reviewed articles and technical papers rather than the injury and fatality data category, based on their publication processes.

RESULTS AND DISCUSSION

Factors Involved in Emergency Vehicle Crashes

The major risk factors for emergency vehicle crashes identified in this study are organized into the following four categories: (a) driver-related factors, (b) task-related factors,

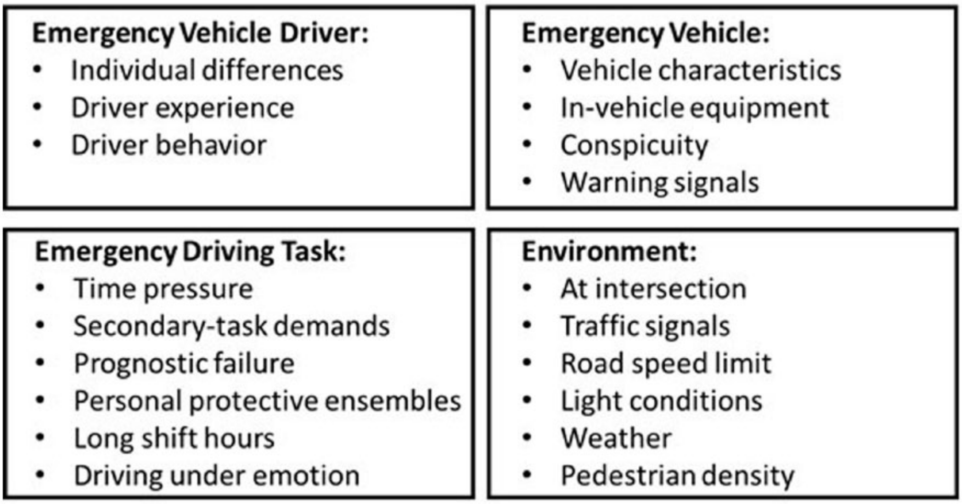

Figure 2. Study results: factors involved in emergency vehicle crashes.

(c) vehicle-related factors, and (d) environment-related factors (Figure 2). The driver-related factors cover the effects of individual differences, driver experience, and driver behavior. The task-related factors refer to a collection of driving and monitoring demands, including steering, controlling speed, monitoring potential threats, communicating with dispatchers, and locating routes, which are characterized with or affected by time pressure, prognostic failure, personal protective ensembles, long shift hours, and driving under emotion. The vehicle-related factors involve emergency vehicle characteristics, in-vehicle equipment, visibility and conspicuity, and emergency vehicles' warning signals (lights and sirens). The environment-related factors include intersections, roadway configurations, and their interactions with light, weather, and pedestrian conditions.

Emergency Vehicle Driver Factors

Emergency vehicle drivers can be affected by a number of personal (intrinsic) factors that could degrade their driving performance. Three critical findings are synthesized below: (a) individual differences, (b) driver experience and training, and (c) driver behavior.

Individual differences. In broad motor vehicle studies, age and gender have been known to be associated with driving behavior and performance. Young drivers (< 25 years) usually drive significantly faster (Boyce & Geller, 2002; Liu, 2007), are more likely to be involved in aggressive and inattentive driving (Shinar & Compton, 2004; Staplin, Lococo, Byington, & Harkey, 2001; Yang & Najm, 2007), and are more likely to be involved in more severe crashes (Paleti, Eluru, & Bhat, 2010). Older drivers (approximately > 60 years) may face age-related physical and cognitive declines with respect to judgement and decision making (Braitman, Kirley, Ferguson, & Chaudhary, 2007), peripheral vision and visual acuity (Bao & Boyle, 2009; Ho, Scialfa, Caird, & Graw, 2001; Maltz & Shinar, 1999), range of body motions—especially neck and head movements (Isler, Parsonson, & Hansson, 1997; Staplin, Lococo, McKnight, McKnight, & Odenheimer, 1998), multitasking capability (Romoser, Pollatsek, Fisher, & Williams, 2013), and reaction time (Staplin et al., 2001). Older drivers are more often involved in crashes in complex environments, for example, signalized intersections and high traffic density areas (Cantin, Lavallière, Simoneau, & Teasdale, 2009; Horberry et al., 2006). Male drivers are more likely to be involved in high-speed driving and have high risk-taking driving behaviors (Liu, 2007; Savolainen et al., 2009; Tay & Rifaat, 2007), while female drivers are more likely to brake to reduce driving speed or stop their vehicles before an upcoming red signal, and are less likely to disregard yellow traffic signals (Yan, Radwan, & Abdel-Aty, 2005). This information is consistent with the data that more severe crashes are prevalent among male drivers than female drivers (Massie, Green, & Campbell, 1997; Tay & Rifaat, 2007).

In contrast, studies have revealed that aging has little impact on emergency vehicle driving, since most emergency vehicle drivers are well-trained and qualified professionals (Abdelwanis, 2013; Savolainen et al., 2009; USFA, 2014a). Emergency vehicle drivers are generally required to take specific training courses that meet state and federal requirements and meet various professional standards (Savolainen et al., 2009; USFA, 2014a). In addition, such training is regularly repeated to prevent driving skills from deteriorating and to identify unqualified drivers (International Association of Fire Fighters, 2010), although this type of training is not always available or required in all affiliated agencies and departments. Savolainen et al. (2009) reported that between 2004 and 2008, the majority of emergency vehicle drivers in the state of Michigan were between the ages of 25 and 44 years old. On the other hand, Abdelwanis (2013) found that although age was not a significant factor in emergency vehicle crashes, older emergency vehicle drivers (> 50 years) could be more prone to fatal crashes than young drivers. This is in contrast to the findings of aging studies that more severe or fatal crashes occurred among young drivers of general passenger vehicles (Paleti et al., 2010; Tay & Rifaat, 2007). This emergency vehicle crash outcome could be attributed to overconfident driving behavior (USFA, 2002) or an increased risk tolerance due to the previous crash history (Biggers, Zachariah, & Pepe, 1996; Custalow & Gravitz, 2004; Kahn et al., 2001) of some older emergency vehicle drivers rather than their age-related physical and cognitive declines.

Similarly, emergency vehicle driving is little affected by the drivers' gender. An analysis of 11,531 emergency vehicle crashes in South Carolina between 2001 and 2010 showed that 82% of emergency vehicle crashes involved male drivers (Abdelwanis, 2013). The Michigan vehicle crash database during 2004 to 2008 showed that the male to female ratio was 75% to 25% for emergency vehicle crashes (Savolainen et al., 2009). Also, of the emergency medical vehicle collisions in Denver (Colorado) during 1989 to 1997, 82% of medical vehicle drivers were male (Custalow & Gravitz, 2004). Moreover, 93% of LEO fatalities in motor vehicle crashes were males (NHTSA, 2011). While exact numbers or percentages of male drivers of emergency vehicles are uncharted, males are known to dominate the emergency response occupations at 95.5% for firefighters, 87% for police, and 71% for EMS workers (Chapman et al., 2008; FBI, 2014; National Fire Protection Association [NFPA], 2018). In short, the emergency vehicle crash distribution by gender appears to reflect demographic distribution of emergency responders (and thus emergency vehicle drivers). In contrast, males had 3 times the crash rate per 100,000 licensed drivers in year 2016 in general motoring as compared to female drivers at 32.8 to 11.03 (NHTSA, 2017b). In addition, male emergency vehicle drivers are involved in less *severe* crashes than female drivers, which is different from general motoring (Savolainen et al., 2009).

Driver experience and training. More emergency medical vehicle crashes occur among drivers who have less than 3 years of experience (Custalow & Gravitz, 2004). Experienced drivers have improved driving competency with respect to adaptiveness for stress and time pressure, skill to narrow the focus of attention appropriately, use of visual information, precautions for predictable contingencies, and decision-making process (Cavallo & Laurent, 1988; Kontogiannis & Kossiavelou, 1999). However, the USFA (2002) cautioned about overconfidence in driving ability among experienced emergency vehicle drivers, which could stimulate risky driving during ED and lead to crashes.

Emergency vehicle drivers may operate various special vehicles of different sizes and weights. To reduce operational errors, training is thus necessary to familiarize drivers with the characteristics of any type of vehicle (USFA 2002, 2014b). The NFPA Standard 1500 emphasized in Requirements 5.1.1 and 5.1.2 that fire departments must provide appropriate training and education that ensure all fire department members can execute their assigned duties and functions in a safe manner (NFPA, 2001). Many studies identified inadequate vehicle operator training as one of the major contributing factors in emergency vehicle crashes (Custalow & Gravitz, 2004; Kahn et al., 2001; Maguire et al., 2002; Pratt, 2003). They recommended more intensive driver training and education courses to overcome this deficiency.

Driver behavior. Repeated risky driving attitudes and behaviors of emergency vehicle drivers are significant determinants of emergency vehicle incidents (National Volunteer Fire Council, 2016). Emergency vehicle drivers have been often involved in speeding, risky, and aggressive driving (De Graeve, Deroo, Calle, Vanhaute, & Buylaert, 2003; Melby, 2001). These behaviors are strongly associated with urgency of emergency duty resulting in severe time pressure (Clarke, Ward, Bartle, & Truman, 2009; Kahn et al., 2001; Pirrallo & Swor, 1994) and siren syndrome caused by the emergency vehicle drivers who are deluded into a false sense of invincibility with warning lights and sirens (USFA, 2014a). In addition, these driving behaviors could be more aggravated by overconfidence of experienced emergency vehicle drivers (USFA, 2002). An emergency vehicle driver having had a previous crash is an indicator for another crash (Kahn et al., 2001). Biggers et al. (1996) reported that due in part to recidivism, five emergency vehicle drivers were responsible for 88% of all injury crashes involving emergency vehicles in Houston in 1993. Custalow and Gravitz (2004) found that 49% of ambulance drivers who have experienced multiple collisions were responsible for 71% of all ambulance collisions in Denver during the period of 1989 to 1997.

Emergency Driving Task Factors

When responding to emergency calls, emergency vehicle drivers must reach their destination as quickly and safely as possible. For that purpose, emergency vehicles are usually equipped with sirens and warning lights and painted in bright colors with recognizable markings. Per the "code 3 running" protocols, they may drive above speed limits with lights and sirens to reduce travel time. Under these ED conditions, the potential for crashes and injuries increases for emergency vehicle drivers and other vehicle drivers. More emergency vehicle crashes and serious injuries have occurred during ED than non-emergency driving (NED) situations (Becker et al., 2003). Custalow and Gravitz (2004) reported that 91% of ambulance crashes in Denver from 1989 through 1997 occurred during ED. Nevertheless, emergency vehicle crashes during NED are also of concern because they share certain similar contributing factors of emergency vehicle crashes during ED (e.g., day of week and season, atmospheric and roadway conditions, relationship to intersections, and manner of collision) (Pirrallo & Swor, 1994).

Time pressure. Time pressure is considered one of the most hazardous task characteristics of emergency vehicle driving. The perception of urgency often pushes drivers to rush and thus to drive over the speed limit, which may lead to crashes (Clarke et al., 2009; Kahn et al., 2001; Pirrallo & Swor, 1994). In general, high-speed driving is strongly correlated with high crash rates and high severity of crashes. It not only results in increased cognitive demands on a driver in terms of information processing and decision making (Harms, 1989; Savolainen et al., 2009) but also reduces the time available to stop or to maneuver to avoid a crash (Spek, Wieringa, & Janssen, 2006; Summala, 2000). Moreover, high-speed driving at intersections with a long dilemma zone creates traffic conflicts with vehicles approaching in different directions (Gazis, Herman, & Maradudin, 1960; Liu, Chang, Tao, Hicks, & Tabacek, 2007); a dilemma zone is the region on the road before an intersection in which drivers have to decide whether to stop or pass through the intersection before an upcoming red signal. Time pressure often also leads to premature decision making, increases risk tolerance, and impairs cognitive performance and health. In a field experiment, Witzel, Hoppe, and Raschka (1999) reported that the levels of cortisol and adrenocorticotropic hormones (i.e., the stress hormones) of volunteer emergency vehicle riders were 30% higher during ED in comparison with NED. These hormones have been reported to impair cognitive performance (Cho, 2001; Hinkelmann et al., 2009) and increase blood pressure (Fraser et al., 1999; Lundberg, 2005).

Secondary-task demands. Driver distraction away from the primary task of driving is often observed during emergency vehicle driving (Sanquist, Baucum, & Brisbois, 2016; USFA, 2014a). Attentional demands of additional tasks while driving (e.g., conversation, dialing) are known to impair driving performance in both laboratory (Brown, Tickner, & Simmonds, 1969; Horrey & Wickens, 2006; Kaber et al., 2012) and naturalistic environment studies of motoring public (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). Conversation demanding high mental workload (e.g., information processing) could disturb driving, particularly in high traffic density areas (Briem & Hedman, 1995; Nunes & Recarte, 2002). If the secondary task requires eyes to be taken off the road during driving (e.g., looking at occupants, scanning sites), drivers could experience significantly slower response time in maneuvering (Dozza, 2013; Hancock, Lesch, & Simmons, 2003; Horberry et al., 2006; Lamble, Kauranen, Laakso, & Summala, 1999; Summala, Lamble, & Laakso, 1998). The multitasking demands among emergency vehicle drivers (e.g., communicating with dispatchers and occupants, operating equipment, scanning sites) have a negative effect on driving performance that could increase the likelihood of fatal vehicle crashes. In controlled laboratory experiments using a high-fidelity simulator, police officers were found to have greater lane deviation and longer braking reaction times while interacting with a mobile data computer (James, 2015). During 2010 to 2014, the Austin (Texas) Police Department experienced 48 patrol car crashes that were attributed to distracted driving; of the incidents, 69% were associated with interacting with mobile computer terminals, phones, or other on-board equipment (Yager, Dinakar, Sanagaram, & Ferris, 2015). For ambulance driving, inattention was the most frequent cause of crashes during ED at 46% and the second most frequent cause during NED at 23% (Saunders & Heye, 1994). National fatalities involving fire vehicles during 2002 to 2012 showed that 70% of the incidents occurred during ED, and technology in the vehicle was reported as a contributor (Yager et al., 2015). Laboratory experiments showed that drivers are in general aware of distraction effects on performance, but not their own impairment in performance (Horrey, Lesch, & Garabet, 2008). Accordingly, Sanquist et al. (2016) concluded in their critical review that emergency vehicle drivers will not be able to effectively compensate for technology-based distraction.

Prognostic failure. Drivers generally assume that road users will comply with traffic signals, for example, oncoming vehicles will slow down and stop for an upcoming red signal. The compliance assumption is often broken on the road and consequently induces unpredictable traffic conflicts at signalized intersections (Chan, 2006). Emergency vehicle drivers during ED may experience more severe prognostic failures at signalized intersections because they believe that "code 3 running" with lights and sirens entitles them to take the right-of-way (De Lorenzo & Eilers, 1991; USFA, 2014a). When other vehicles fail to yield to them at signalized intersections, emergency vehicle drivers may be forced into unfavorable maneuvers or unavoidable situations that can lead to a crash. Note that other vehicles equally have the right-of-way at a green light until emergency vehicles approach. To minimize the effect of this failure, emergency vehicle drivers are advised to visually confirm that all adjacent vehicles completely stop and ensure that the other vehicles have yielded the right-of-way before passing through intersections (NFPA, 1987; USFA, 2014a).

Personal protective ensembles. Emergency vehicle drivers often drive their vehicles while wearing their heavy and bulky personal protective ensembles for quick actions and responses (USFA, 2014a). However, driving with such personal protective ensembles could disturb a driver's ability to maneuver because wearing heavy protective clothing generally limits the range of body motions (Adams & Keyserling, 1995; Coca, Williams, Roberge, & Powell, 2010; Huck, 1991). Moreover, bunker boots, which have thick platforms, could slow down brake response times and decrease braking accuracy (Sansosti, Rocha, Lawrence, & Meyr, 2016; Warner & Mace, 1974). Wearing heavy personal protective ensembles could also prevent emergency vehicle occupants (including drivers) from using seat belts during emergency vehicle driving (Peterson, Amandus, & Wassell, 2009), and the lack of seat belt use was a key contributor to severe injuries and high fatality rates in emergency vehicle crashes (Abdelwanis, 2013; Studnek & Ferketich, 2007; USFA, 2014a). Routley (2006) found that approximately 60% of firefighters were not belted while responding to emergency. Recent research has shown that seat belt configurations in fire apparatus do not adequately accommodate the body dimensions of firefighters, particularly when they are wearing turnout gear (Hsiao, Whitestone, Wilbur, Lackore, & Routley, 2015). Updated specifications from this research are expected to lead to more comfortable seat belt systems in fire trucks, removing some of the barriers to belt use by firefighters.

Long shift hours. While emergency vehicle drivers may not be required to drive for long hours (except for police patrol drivers), they usually have long work shifts (Lackore, 2004). Firefighters and emergency medical technicians typically work 24-hour shifts (Dobson et al., 2013; Mock, Wrenn, Wright, Eustis, & Slovis, 1999; Peleg & Pliskin, 2004; Ranby et al., 2011), and LEOs work up to 12-hour shifts (Vila, 2006). Working long hours is likely to cause physical or mental stress, which can lead to fatigue and drowsiness during emergency vehicle driving (Elliot & Kuehl, 2007). Fatigued and drowsy drivers may experience delayed reaction time and longer time to recognize hazards on the road (Brown, 1994; USFA, 2014a). In addition, fatigue reduces visual efficiency and obstructs decision making, as demonstrated by overestimating the distance to roadside traffic signs and larger variation in lane position (Liu & Wu, 2009). The most serious effect of fatigued and drowsy driving is that drivers may not recognize these symptoms until it is too late (Brown, 1994).

Driving under constraint and emotion. Emergency vehicle drivers are exposed to a variety of stressors. In responding to emergency calls, they need to be prepared to drive at any time and often in unfamiliar areas. They frequently operate during disasters, adverse weather, or severe environmental conditions. Moreover, they repeatedly face sick or injured people at crash or disaster scenes. Thus, emergency vehicle drivers could be in situations where information is constrained (such as bad visibility at city intersections, hazardous rural driving conditions, and risks of contracting an illness), which may jeopardize their decision making and may carry emotional burdens (Custalow & Gravitz, 2004; Heyward, Stanley, & Ward, 2009; Savolainen et al., 2009). They may fall into confusion and disorder because of exposure to highly unpredictable circumstances (Abdelwanis, 2013). These stressful driving conditions naturally have negative impacts on a driver's performance. Previous studies found that stress restricts humans from fully exploring important cues in information processing and degrades the capacity of working memory, which may contribute to premature closure in evaluating alternative options (Edland & Svenson, 1993; Hamilton, 1982; Kerstholt, 1994). Also, driving in unfamiliar areas could cause abnormal behaviors, such as improper lane change and sudden stop for turning, due to the lack of information (Yan, Radwan, & Abdel-Aty, 2005).

Emergency Vehicle Factors

Most emergency vehicles are specialized vehicles designed to enable and support specific operations and functions. Some emergency vehicles may be based on regular passenger and commercial vehicles, but they are configured for enhanced performance and with specialized equipment. Due to their unique design or modified characteristics, most emergency vehicles may perform differently when driven as compared to regular passenger or commercial vehicles. Furthermore, due to their unique functions and associated driving patterns, sharing the road with emergency vehicles can be a challenge to both emergency vehicle drivers and other road users.

Vehicle characteristics. Emergency vehicles differ from other passenger vehicles in structural and functional characteristics, particularly in weight and size. The weight of an emergency vehicle can be threatening to occupants of other vehicles during a crash, while its size can be an extra protection of emergency vehicle occupants if a crash occurs (Robertson & Baker, 1976). Police vehicles are relatively light and small in comparison with fire apparatus (Savolainen et al., 2009). They are generally the first vehicles to respond to a wide range of emergencies, including pursuits. To improve their power and dynamics under typical conditions, police vehicles often incorporate various functional modifications, such as upgraded engines and braking systems, enabling them to have quicker stopping and acceleration capabilities and agile evasive maneuverability (USFA, 2014a). Consequently, police vehicles are more often involved in crashes caused by speeding and also prone to more severe injuries as compared to other emergency vehicles (Alpert, 1997; Savolainen et al., 2009).

Heavy and large emergency vehicles (e.g., fire trucks and ambulances) are often hard to control on the road and thus require special maneuvering skills for drivers (Horberry et al., 2004). In addition, heavy and large emergency vehicles generally have a higher center of gravity than smaller vehicles (Custalow & Gravitz, 2004). Vehicles with a higher center of gravity produce a larger lateral momentum during turning or on a curved road, which could impede a driver's maneuvering and make the vehicle uncontrollable (USFA 2002, 2014a). A solution to the issue is to operate and turn the vehicle slowly (White & Eccles, 2002). However, a slow turning speed can increase the chances for traffic conflicts, especially with oncoming vehicles during turning phases at intersections. Studies have reported that angular crashes are more likely to occur than other types of crashes among emergency vehicles (Abdelwanis, 2013; Kahn et al., 2001; Ray & Kupas, 2007).

In addition, heavy vehicles have low acceleration and deceleration capabilities due to their mass (Bryant, Rakha, & El-Shawarby, 2015; Gates, Noyce, Laracuente, & Nordheim, 2007; Gates & Noyce, 2010; Horberry et al., 2004). For some fire trucks, the mass of vehicle structures behind occupant compartments could also produce additional forward and backward forces during driving (e.g., water surge in a tank), which make vehicle operation a challenge (USFA, 2002). In fact, single-vehicle crashes (e.g., collision with an object) are one of the most frequent crash types among emergency vehicles, and the incidents often are very serious (Abdelwanis, 2013). As reported in a study on 1,440 fatal vehicle crashes including tractor-trailers, heavy structures behind occupant compartments could increase the impact forces on the driver when colliding with objects on the road (Robertson & Baker, 1976). Fire truck and ambulance drivers are facing the same risk. On the aspect of safety of other road users, heavy vehicle crashes are reported to cause more severe injuries and fatalities to drivers of other vehicles (Campbell & Reinfurt, 1973; Custalow & Gravitz, 2004).

Moreover, due to their size, large emergency vehicles could adversely affect other road users. In a study on rear-end collisions based on the NHTSA General Estimates System (GES), light-duty trucks were reported to occlude the vision of adjacent vehicle drivers (Abdel-Aty & Abdelwahab, 2004), which limits their acquisition of visual information, such as traffic signal change and traffic situations ahead (Werneke & Vollrath, 2012). This may also lead drivers of small cars to maintain shorter distances with the leading vehicle (Sayer, 2000), which reduces the available time of the small car driver to respond to sudden events (e.g., sudden braking of the leading vehicle) and thus increase the likelihood of rear-end crashes. In addition, large vehicles could cause cognitive confusion among adjacent road users. While large vehicles are easily detectable, it takes more time for adjacent drivers to assess the speed and length of a large vehicle than a small car, and the assessment accuracy is typically lower, which can adversely delay their decision making (Hurt, Ouellet, & Thom, 1981). The size (dimension) effect of emergency vehicles on responder safety and other road user safety in terms of visual-information acquisition is not well reported. Based on the reported adverse effect of light-duty trucks and tractor-trailers on other road users' acquisition of visual information, sharing the road with emergency vehicles can be a challenge to both emergency vehicle drivers and other road users.

In-vehicle equipment. Emergency vehicle drivers often are required to interact with in-vehicle equipment (e.g., radio transmitter, warning devices, laptop computer, and map navigator) during driving (USFA, 2014a). Operating equipment while driving could have greater negative impacts than any other multitasking activity because it usually requires eyes to be taken off the road. Simulator studies have shown that drivers are significantly slower in responding while looking away from the road (such as use of a phone, operating an entertainment system, and adjusting a digital display) (Hancock et al., 2003; Horberry et al., 2006; Summala et al., 1998). Specifically, attending to secondary tasks and eyes-off-road significantly slow down response times in naturalistic tests by 16% and 29%, respectively (Dozza, 2013). While SOPs for emergency vehicle operation recommend that a second person operate in-vehicle equipment when the vehicle is in motion, it is still common to see emergency vehicles (especially police vehicles) that are occupied by a single individual (USFA, 2014a).

Conspicuity. To improve conspicuity on the road, emergency vehicles are often painted with light colors (e.g., white, yellow lime) and marked with retroreflective materials and/or fluorescent colors (USFA 2002, 2014a). Nevertheless, detecting emergency vehicles on the road remains a challenge for the other road users because the efficacy of the emergency vehicle colors and markings is usually a function of environmental conditions (USFA, 2014b). In general, light vehicle colors (e.g., white, yellow lime, yellow) are more visible during daytime under clear weather (USFA, 2014b). The influence of vehicle color on visibility is significantly reduced in adverse light conditions (Lardelli-Claret et al., 2002), particularly to small emergency vehicles during NED at night. Similarly, retroreflective markings are only effective at night and rely on an external light source (USFA, 2002). Fluorescent materials enhance the conspicuity of an object during the daytime (Buonarosa & Sayer, 2007), but they offer no additional benefit at night because fluorescent colors only interact with ultraviolet radiation (USFA, 2014a).

Warning lights and sirens. Warning lights and sirens are used to announce the presence of an emergency vehicle in order to request the right-of-way and negotiate traffic for minimizing travel time during ED (De Lorenzo & Eilers, 1991; Saunders & Heye, 1994). They could, however, adversely affect both emergency vehicle drivers and nearby drivers. They have a strong influence on drivers' vision, hearing, mental state, and physical and physiological systems, which could disturb driving performance regardless of exposure duration (De Lorenzo & Eilers, 1991; Flesch, Tubbs, & Carpenter, 1986; USFA, 2014a).

Strobe lights could impede a person's vision (particularly at night), induce driver distraction, and trigger rare bodily reactions such as an unusual feeling, involuntary twitch, or full-blown seizure due to photosensitive epilepsy (USFA, 2014a), although emergency vehicles typically have much lower flash rates than the triggering range of 10 to 20 hertz frequency. Studies have warned that an extended use of warning lights is likely to contribute to adjacent vehicle crashes (Saunders & Heye, 1994; USFA, 2002).

Warning sirens are generally designed to overcome the ambient noise produced by the road, car radios, ventilation fans, and so forth, and thus are very loud (De Lorenzo & Eilers, 1991). They often limit emergency vehicle drivers' acquisition of auditory information from dispatchers, passengers, or surrounding vehicles. In addition, long-term exposure to sirens could damage the hearing of emergency vehicle drivers (De Lorenzo & Eilers, 1991; Flesch et al., 1986). Although hearing is not as important for driving as vision (Schiff & Oldak, 1990), it is regarded as a primary warning sense (Patterson & Mayfield, 1990) because people respond to auditory stimuli faster than visual stimuli (Liu, 2001) and are immediately aroused by loud auditory signals (Sanders, 1975). Moreover, sirens may delude emergency vehicle drivers into a false sense of invincibility, which is often associated with an adrenaline rush (USFA, 2014a). An adrenaline rush is characterized by a massive surge of the hormone epinephrine into the bloodstream, which allows people to actively face a stress and conquer it (Wong, Tai, Wong-Faull, Claycomb, & Kvetňanský, 2008). People in this state generally have a faster or irregular heartbeat, troubled breathing, feelings of over-excitement or anxiety, and stronger muscle performance (Cannon & de la Paz, 1911), which could cause abnormal behaviors. Drivers with high epinephrine may also become more aggressive and take more risks, which can result in risky or careless driving (Dula, Geller, & Chumney, 2011; Netter & Neuhäuser-Metternich, 1991). Such aggressive and abnormal driving behaviors of emergency vehicle drivers have frequently been observed on the road (De Graeve et al., 2003; Melby, 2001), and these acts are often complicated by inattention of the drivers and failure to yield by other drivers, resulting in emergency vehicle crashes (Saunders & Heye, 1994).

Environment Factors

The performance of an emergency vehicle driver is influenced by a variety of environmental factors, including roadway design, traffic signals, weather and road conditions, and others. While the effect of each factor may be small, the interaction between the factors could have significant effects on a driver's performance. Environment factors have similar effects on public motoring and emergency vehicle driving. The situation might be aggravated when driving emergency vehicles.

Roadway design at intersection. The size of intersections has a significant impact on vehicle safety. Intersections with more lanes increase the likelihood of traffic conflicts; a vehicle travels longer distances in the box junction (a place where two roads cross), encountering more traffic that travels in the same and different directions (Poch & Mannering, 1996; Polders et al., 2015; Wang, Abdel-Aty, & Brady, 2006). Heavy and large vehicles that cannot make rapid maneuvers (such as deceleration) may experience additional challenges while passing through such intersections. Florida traffic accident data affirmed that rear-end striking risk at intersections is increased with increment of vehicle size (Yan, Radwan, & Birriel, 2005). Large vehicles may also encounter more traffic conflicts when making a turn due to their increased turning radius. In addition, vehicles driving downhill toward intersections have larger forward momentum and thus are harder to maneuver and require more time to stop (Yan, Radwan, & Birriel, 2005). The situation might be aggravated when driving heavy emergency vehicles. Skewed intersections (i.e., intersecting angle < 90°) are also hazardous (Roess, Prassas, & McShane, 2004). The inertia of a vehicle during a turn may result in a rollover. The risk is even more serious in emergency vehicle driving because heavy and large emergency vehicles typically have a higher center of gravity (Custalow & Gravitz, 2004; USFA, 2014a).

Traffic signals. Traffic signals are installed to lessen the number of traffic conflicts and increase traffic safety at intersections (Roess et al., 2004). Yet signalized intersections are considered the most complex road settings for many road users to navigate, especially when other drivers fail to comply with traffic signals (Devlin, Candappa, Corben, & Logan, 2011; Ragland, Arroyo, Shladover, Misener, & Chan, 2006). More emergency vehicle crashes have occurred at intersections than other places (Elling, 1989; Ray & Kupas, 2007). The traffic signal related dilemma zone, red light running, and traffic signal logic are among the issues common to both emergency vehicle driving and general motoring but much more risky for emergency vehicle driving.

A dilemma zone is the region on the road that forces drivers to decide whether to stop or pass through an intersection before an upcoming red signal (Gazis et al., 1960). If a vehicle within the dilemma zone stops abruptly, a sudden conflict could occur with following vehicles, which may result in rear-end crashes (Polders et al., 2015; Richards, Michaels, & Campbell, 2005). If the vehicle enters a box junction late, it may run a red light, which can result in angular crashes (Bonneson, Zimmerman, & Quiroga, 2003; Gazis et al., 1960; Polders et al., 2015). High-speed driving creates a longer dilemma zone at signalized intersections because drivers must make the decision to stop or proceed farther away from the stop bar that indicates the entrance of the box junction (Liu et al., 2007; Papaioannou, 2007). Emergency vehicle driving during ED is typically in a high-speed mode, which lengthens dilemma zone. In addition, fire trucks and ambulances are associated with an increased length of dilemma zone at signalized intersections for their longer length (Bonneson et al., 2003). Moreover, their low acceleration/deceleration capability requires longer time and distance to gain speed or stop and thus elongates their dilemma zones.

The risk of red light running (traffic signal violation) at signalized intersections needs to be appraised from two aspects: (a) emergency vehicles become red light runners and (b) emergency vehicles face other red light runners. Vehicles with high approaching speed are more likely to run red lights because high-speed driving reduces their available time to stop (Bonneson, Zimmerman, & Brewer, 2002; Gates & Noyce, 2010). In addition, field studies showed that heavy vehicles, particularly tractor-trailers, were 3.6 times more likely to commit red light running compared with passenger vehicles (Gates & Noyce, 2010). Accordingly, fire trucks and ambulances are more likely to go through than to stop at the end of a yellow light due to their high inertia and low deceleration capability. The increased risk of red light running in emergency vehicles is likely to create more unpredictable traffic conflicts in box junctions and thus increase the probability of angular crashes (Chin, 1989). However, these behaviors should be differentiated from authorized emergency vehicle crossing at intersections during ED. Emergency vehicle drivers can also encounter other red light runners at intersections. Red light running is typically difficult for other drivers to predict (Devlin et al., 2011), and thus a heavy emergency vehicle driver's ability to respond to a red light runner could be substantially impaired.

The length of a yellow light phase has a negative relationship with the length of the dilemma zone. Field experiments demonstrated that too short a yellow light phase (approximately < 3.5 seconds) increased the length of the dilemma zone and promoted more red light running (Bonneson & Son, 2003; Retting & Greene, 1997). An increase of 1.0 second in yellow duration decreased the frequency of red light violations by 50% (Bonneson & Zimmerman, 2004). The current length of the yellow light phase, recommended by the Institute of Transportation Engineers (ITE), is based primarily on passenger vehicles and their efficient traffic flow, but is as much as 1.5 seconds less than the optimal length for large vehicles such as truck trailers as reported in laboratory driving simulator studies (Bryant et al., 2015), and thus fire trucks and ambulances. In addition, the number of traffic signal phases per cycle may affect emergency vehicle driving at signalized intersections. Most vehicle crashes at signalized intersections occur as traffic signals change because this is the moment more dilemma zones appear (Chin & Quddus, 2003). With more dilemma zones, emergency vehicle drivers may need to use brakes more frequently around intersections, which may lead to rear-end crashes, and they may encounter more vehicles committing red light running, which can lead to angular crashes (Chin, 1989).

Road speed limit. Emergency vehicle crashes have significant relationships with road speed limits. Savolainen et al. (2009) and Abdelwanis (2013) found that more severe emergency vehicle crashes occur at intersections on streets and roads with higher speed limits. In particular, injuries tend to be more severe when emergency vehicles during ED are involved in angular collisions (Abdelwanis, 2013). In general motoring incidents, high speed increases physical impacts in the event of crashes (Navon, 2003). Drivers are more likely to commit serious mistakes (especially red light running) at higher road speed limits due to cognitive overloads in perception and decision making (Harms, 1989; Navon, 2003) and reduced time available to stop or maneuver (Spek et al., 2006; Summala, 2000). Emergency vehicle driving at high speed carries the same risks, and emergency vehicles' large forward momentum can be more detrimental in an accident (Robertson & Baker, 1976; USFA, 2002). Conversely, a majority of emergency vehicle crashes occur when road speed limits are less than 50 miles per hour (Abdelwanis, 2013; Pirrallo & Swor, 1994; Saunders & Heye, 1994) in that a large percentage of emergency vehicle driving occurs on roads with low speed limits (Savolainen et al., 2009).

Other environment-related factors. Emergency vehicle driving is exposed to other environmental factors, such as light conditions, weather, and pedestrian engagement (Pirrallo & Swor, 1994). Data on fatal emergency crashes in South Carolina during 2001 to 2010 revealed that 54% of the fatal emergency vehicle crashes occur during nighttime (Abdelwanis, 2013). NHTSA reported that 77% of vehicle crashes with LEO fatalities occurred during the evening and midnight shifts (NHTSA, 2011), and the Fatality Analysis Reporting System and the Crashworthiness Data System showed that 72% of fatal crashes related to police pursuit occurred during nighttime (Rivara & Mack, 2004). In addition, data from the Pennsylvania Department of Transportation indicated that 33% of ambulance crashes occurred between 6:01 PM and 6:00 AM (Ray & Kupas, 2007). In general, night driving obscures drivers' vision, which not only slows drivers' reaction time on the road (Corfitsen, 1994; Dozza, 2013) but also hinders drivers from noticing traffic signals or other approaching road users (NHTSA, 2011; Tay & Rifaat, 2007; Yan, Radwan, & Birriel, 2005). On the contrary, the majority of nonfatal emergency vehicle crashes occur during daytime (Custalow & Gravitz, 2004; Elling, 1989; Pirrallo & Swor, 1994; Ray & Kupas, 2007; Savolainen et al., 2009). This is because the daytime traffic volumes are usually greater (Yan, Radwan, & Birriel, 2005).

Inclement weather (e.g., snow or rain) may influence emergency vehicle driving (USFA, 2014a). For general motoring, adverse weather not only reduces vehicle visibility but also obscures a driver's vision on the road (Mueller & Trick, 2012). In addition, steering control could be adversely affected by inclement weather due to road surface conditions (USFA, 2014a). A meta-analysis of literature on effect of adverse weather on vehicle crashes indicated that snow increased the crash rate by 84% and the injury rate by 75%, while rain increased the crash rate by 71% and the injury rate by 49% (Qiu & Nixon, 2008). However, the majority of emergency vehicle crashes occur on dry roads in clear weather (Custalow & Gravitz, 2004; NHTSA, 2011; Ray & Kupas, 2007; Saunders & Heye, 1994; Weiss, Ellis, Ernst, Land, & Garza, 2001). This outcome can be explained in three ways. First, there are typically more clear weather days. Second, traffic volumes decrease in inclement weather, which could reduce the likelihood of traffic conflicts on the road (Keay & Simmonds, 2005; Maze, Agarwai, & Burchett, 2006). Third, drivers usually reduce their vehicle speeds and drive more cautiously on adverse roadway surface conditions.

In 2015, there were 5,376 pedestrians killed (NHTSA, 2017a), and most fatalities occurred at nonintersections (72%) and in the dark (70%). Of the 4,851 cases involving single vehicles, 47% were hit by trucks and buses, 43% by passenger cars, and 10% by other vehicles. Speeding, trucks, and pedestrian fault were also found to significantly increase the probability of fatal injury for pedestrians in pedestrian-vehicle crashes (Kim, Ulfarsson, Shankar, & Mannering, 2010). High pedestrian density areas, such as commercial accommodations, schools, and amusement and gaming centers, are considered the most hazardous areas for pedestrian crashes (Miranda-Moreno, Morency, & El-Geneidy, 2011; Ukkusuri, Miranda-Moreno, Ramadurai, & Isa-Tavarez, 2012). Pirrallo and Swor (1994) reported that approximately 59% of fatal nonmotor-vehicle to ambulance crashes in the United States involved pedestrians, and an equal number of pedestrians were struck by ambulances during ED and NED. Detail information specific to pedestrian fatalities and injuries due to emergency vehicles is uncharted.

REGULATIONS AND TECHNOLOGY TO CONTROL AND PREVENT EMERGENCY VEHICLE CRASHES

While many government agencies, academic institutions, public and private research organizations, labor organizations, and professional societies have devoted their efforts to general vehicle safety research, the safety research on emergency vehicle driving remains limited. A primary source of information for prevention of emergency vehicle crashes is standards developed by the NFPA and the USFA (NFPA, 2016; USFA, 2009, 2014a).

Regulations, Policies, and Standards

The first standard on firefighter professional qualifications was adopted by the NFPA in 1976. They consecutively published NFPA 1001, Standard for Fire Fighter Professional Qualifications, and NFPA 1002, Standard for Fire Apparatus Driver/Operator Professional Qualifications, and officially organized the recommended training requirements for fire apparatus drivers (NFPA 1976a, 1976b). In 1987, the NFPA published NFPA 1500, Standard on Fire Department Occupational Safety and Health Program (NFPA, 1987). This was the first consensus standard to include emergency apparatus safety, safe operating procedures, and the qualifications of the drivers (Stull & Stull, 2008).

In 2000, the NFPA standardized the maintenance guidelines for fire apparatus in NFPA 1915, Standard for Fire Apparatus Preventive Maintenance Program, but NFPA 1915 did not cover the compatible guidelines for emergency medical service and police vehicle maintenance (NFPA, 2000).

The USFA released its “safety operation of fire tankers” in 2002 (USFA, 2002). The guide provided information on physical features and the impact of heavy emergency vehicles on the road and specified a training and education program for drivers and safe driving practices. In collaboration with the NHTSA and the U.S. Department of Transportation (DOT) Intelligent Transportation Systems (ITS; i.e., the advanced communication technologies to improve transportation safety and productivity), the USFA published the *Emergency Vehicle Safety Initiative* in 2004, which identified a number of major safety issues (e.g., intersection traverse, speeding, inclement weather, driver distraction, siren syndrome, and fatigue) among emergency vehicles responding to or returning from emergency areas. The initiative also provided relevant safety practices, guidelines, and technologies (USFA, 2004). In 2010, the International Association of Fire Fighters (IAFF) and the USFA published the *Best Practices for Emergency Vehicle and Roadway Operations Safety in the Emergency Services*, which provides the latest safety practices for emergency vehicles (IAFF, 2010).

Some science-based recommendations for emergency vehicle design have also been developed. The International Fire Service Training Association (IFSTA) and the USFA reported that fluorescent yellow-green and orange provide higher visibility for emergency vehicles during daylight driving on the road (USFA, 2009). They also suggested that distinctive logos or emblems on retroreflective materials (background) could improve the visibility and recognition of emergency vehicles. NFPA 1901, Standard for Automotive Fire Apparatus, recommended that reflective striping be used on all four sides of the apparatus and restricted the color to red alternating with either yellow, fluorescent yellow, or fluorescent yellow-green (NFPA, 2016). NFPA 1901 and the Society of Automotive Engineers (SAE) document J595 contain standardized warning light designs for emergency vehicles (NFPA, 2016; SAE, 2014). NFPA 1901 and SAE recommend the combination of colors (including white, yellow, red, and blue) and a flash rate between 1.0 and 4.0 hertz to improve the visibility of the warning lights. The University of Michigan Transportation Research Institute (UMTRI) also provided information on the warning light design (UMTRI, 2008). They suggested to use different intensity levels of the warning lights depending on light conditions (e.g., high intensity during daylight driving) and employ more blue color overall in order to improve the visibility of emergency vehicles and mitigate interference in driver vision. NFPA continues to update its design requirements for new fire apparatus in NFPA 1901 (NFPA, 2016). The updated standard emphasizes that all emergency vehicles exceeding a gross vehicle weight rating of 32,000 pounds must be equipped with antilock braking systems to improve vehicle control and decrease stopping distance.

Technology Support

Emergency vehicle driving may benefit from several advanced roadway technologies. The Federal Highway Administration (FHWA) introduced the automated vehicle location and computer-aided dispatch systems, which use traffic surveillance and detection technology to enhance emergency vehicle roadway safety (Bunch et al., 2011). In cooperation with emergency dispatchers, the systems identify incident situations and locations, and provide safe and quick routes for emergency responders. Bunch et al. (2011) reported that approximately 48% of dispatchers and 88% of responders in metropolitan areas utilized the two systems in 2011. Also, traffic signal preemption systems have enabled emergency vehicles to obtain the right-of-way at intersections during ED (FHWA, 2009); these systems allow emergency vehicle dispatchers and responders to directly or indirectly control traffic signals at intersections and crosswalks, which reduces emergency response time and improves traffic safety during ED. In addition, Traffic Management Centers (TMCs), operated by various agencies in the U.S. (e.g., state DOT, FHWA), monitor traffic signals, intersections, and roadways through cameras, sensors, and other advanced roadway technologies. They also proactively manage the traffic flows to reduce traffic conflicts and congestion on the road, which is helpful for emergency vehicle driving (USFA, 2014a).

DIRECTIONS FOR FUTURE RESEARCH

This article has identified and reviewed a number of factors associated with emergency vehicle crashes. Understanding these factors and their antecedents will be helpful for modifying certain driver, task, vehicle, and environmental conditions and thus help mitigate emergency vehicle crashes. The following are some knowledge gaps to be resolved for improving our understanding of the mechanism of emergency vehicle crashes and for developing strategies to proactively enhance emergency vehicle safety on the road. These knowledge gaps (or research concepts), derived from the aforementioned literature analyses, are proposed to inspire more ideas from readers.

Driving Behaviors and Patterns of Emergency Vehicle Drivers

This literature review revealed differences between emergency vehicle drivers and general motor vehicle users. Individual physical differences (e.g., age, gender) of emergency responders played little role on incidents of emergency vehicles. Overconfidence in driving among experienced emergency vehicle drivers was reported to contribute to risky behavior during ED, and the "code 3 running" thinking intensified risky driving attitudes. Statistics showed that training alone is insufficient for reducing dangerous driving attributable to emergency vehicle crashes (Custalow & Gravitz, 2004; Savolainen et al., 2009; USFA, 2014a). Studies of root causes of the risky behaviors and creative control measures through psychosocial assessments and technology simulations may be helpful to develop strategies that are more effective for mitigating the adverse effects.

Coping with Red Light Running in Emergency Vehicle Driving

Emergency vehicle drivers are exposed to the hazard of red light running on the road during ED. They also often face other red light runners at signalized intersections (Devlin et al., 2011), especially at high traffic density areas (Bonneson & Son, 2003; Noyce, Fambro, & Kacir, 2000; Porter & England, 2000). In addition, heavy emergency vehicles are likely to commit red light running during NED due to their large masses and low deceleration capabilities. The current length of the yellow light phase is based primarily on passenger vehicles and is as much as 1.5 seconds less than the optimal length for fire trucks and ambulances. "Extension of the yellow phase alone may not eliminate all dilemma zones at intersections with high-speed approaching flows" (Liu et al., 2007). Research needs to be done proactively to better identify emergency vehicle drivers' perception and awareness in committing red light running and how they cope with red light runners on the road.

In a field experiment, a green-phase extension system was tested to decrease 54% of rear-end and right-angle collisions (Zegeer & Deen, 1978). The system includes presence-detection loops in the pavement preceding the intersection that transmit messages to a receiver in the signal control box. An extension of the green phase occurs only if a vehicle is passing over the detector within an interval that has been predetermined as the dilemma zone. Building on the concept, traffic signal preemption systems have been used in some cities which enable emergency vehicles to obtain the right-of-way at intersections during ED (FHWA, 2009). Some challenges remain and emergency vehicles crashes have occurred at intersections when multiple vehicles respond to the same mishaps. As sensing and computing technologies have advanced significantly during the past decade, cost-benefit studies on expanding these red light running control technologies are warranted to enhance emergency vehicle driving safety. Crashes associated with red-light running have a societal cost. It was estimated to be $2 billion each year in Texas (Bonneson et al., 2003).

Different Driving Behaviors of Emergency Vehicle Drivers Between ED and NED

Although more emergency vehicle crashes and serious injuries have occurred during ED than NED situations and their causes are different at a micro level (e.g., driver error type, driving behavior) (Becker et al., 2003), similar attributable causes for crashes during ED and NED are found at a macro level (e.g., manner of collision, incident locations, and time) (Pirrallo & Swor, 1994). It is unclear whether a carryover effect exists from ED to NED and at what rate. Further research can be done to investigate carryover effects for developing collateral strategies to more effectively control and prevent emergency vehicle crashes.

Distraction in Emergency Vehicle Driving

Existing interventions for reducing driver distraction in emergency vehicle driving focus on administrative controls, such as the development of regulations and policies (e.g., the use of a second person for secondary tasks or the limited use of single-driver vehicles during ED) (USFA, 2014a). Studies on levels of distraction and engineering interventions among emergency vehicle drivers are limited. Simulator studies of public motoring drivers have shown a critical 15% increase in nonresponse to stop lights in the presence of an in-vehicle phone distraction (Hancock et al., 2003) and significantly slower in maintaining speed and reacting to a pedestrian crossing in the presence of interacting with an entertainment system (Horberry et al., 2006). Naturalistic tests also reported that conducting a conversation and eyes-off-road slowed down response times by 16% and 29%, respectively (Dozza, 2013). Furthermore, in an on-road experiment in Finland on driving while dialing a numeric keypad or performing a memory task, drivers' detection ability was impaired by 0.5 second in terms of brake reaction time and 1 second in terms of time-to-collision (Lamble et al., 1999). Undoubtedly, emergency vehicle drivers are facing greater challenges for the amount of secondary-task demands they have encountered while driving. Furthermore, the fatigue from long driving hours, irregular shifts, and emotional stress on responders can further complicate the challenges.

As technologies advance, several approaches warrant further investigation and consideration. First, a systematic classification of the sources of driver distractions (big data) during emergency vehicle driving can be done, and high-demand secondary tasks can be assigned to a nondriver accordingly. Second, advanced communication technologies and improved user-interface designs (based on human factors principles) for vehicle operation can be developed and evaluated for user acceptance to reduce the loads of secondary tasks. Third, a variety of advanced driver assistance systems (ADAS) are quickly becoming common among many passenger and commercial vehicles. Such systems include collision prevention, vehicle speed monitoring and controlling, braking assistance and antirollover systems, lane and side assistance, backing assistance, driver state and behavior monitoring (e.g., eyes off the road, distraction, drowsiness, risk-taking behaviors), and driver communication assistance (National Safety Council, 2016). Some of these systems provide warnings and rely on the driver's adequate response, while others automatically intervene in the control of the vehicle. Research can be done on which types of ADAS are most effective in reducing secondary-task demands and mitigating crashes involving emergency vehicles during ED and NED.

Furthermore, the quick growth of self-driving (autonomous) vehicles may introduce new challenges to emergency vehicle drivers in sharing the road with other vehicles with no, partial, or full automation, especially during the transition between partial and full automation of the individual vehicles. On the other hand, opportunities exist to implement full autonomy in emergency vehicle operation to reduce or eliminate distracted driving. Another opportunity is being created by the fast-developing "connected vehicles" technology, which allows vehicles to "talk" to each other on the road by sharing data, such as direction, location, and speed. Integrating emergency vehicles into a network of vehicle-to-vehicle and vehicle-to-infrastructure communication-enabled systems will allow more effective and safer performance by reducing or eliminating most of the traffic conflicts during emergency response. A cost analysis and technology simulations can be undertaken to compare the "smart-town" concept with existing traffic signal preemption systems that enable emergency vehicles to obtain the right-of-way at intersections during ED.

Vehicle Design and Sirens

Emergency vehicles have inherent design issues due to their size and weight (e.g., high center of gravity, low acceleration/deceleration), which could adversely affect driving safety. The current emergency vehicle designs still have room for improvement in the structures and functions (e.g., stability, weight, braking). In addition, more studies on in-vehicle equipment design (e.g., seats, seat belts, radio transmitter, warning devices, navigation system) are needed to minimize attentional overload and improve the safety of drivers and occupants, based on human factors principles. Furthermore, sirens play an important role in emergency vehicle driving as a primary warning tool. Their loudness can interrupt the communication between dispatchers and emergency vehicle drivers, and long-term exposure to sirens could impair hearing (De Lorenzo & Eilers, 1991; Flesch et al., 1986). Research on intensity of sirens and development of intelligent sound controls could be helpful for mitigating side effects of loud sirens. In addition, as digital technologies advance, different fire departments and ambulance corps may have different siren systems. They are relatively free to have their own systems (Rubin and Howett, 1981). The variety of messages used by the emergency vehicles may be familiar to local drivers but may be unacquainted to others. A study for effectiveness of siren messages may be warranted.

Pedestrian Crash

Pedestrian crashes are one of the prevalent types of vehicle crashes. Many nighttime crashes with pedestrians are associated with the visual limitations that drivers experience at night. The visual challenges are exacerbated when pedestrians wear low-reflectance clothing and when drivers experience glare (Tyrrell, Wood, Owen, Borzendowski, & Sewall, 2016). Studies also have shown that larger vehicles are involved in more pedestrian fatalities than smaller vehicles per vehicle years registered (Kim et al., 2010; Robertson & Baker, 1976), and larger and higher hoods were attributed to compromised pedestrian visibility to drivers. Pirrallo and Swor (1994) reported that approximately 59% of fatal non-motor-vehicle to ambulance crashes in the United States involved pedestrians. Several research topics are warranted for pedestrian-emergency-vehicle crash control, given the risk factors of vehicle size (NHTSA, 2017a) and high pedestrian density areas (e.g., commercial accommodations, schools, and residential complexes) that emergency responders have encountered (Miranda-Moreno et al., 2011). First, while retroreflective markings on the extremities have been suggested for pedestrians to attract the attention of drivers (Tyrrell et al., 2016), other strategies to reduce emergency vehicle crashes with pedestrians (e.g., in-vehicle assistance systems) remain to be explored. Research can be done through lab simulations as current injury and fatality data systems do not provide sufficient information to comprehend the causes. Studies also can be done to evaluate the effectiveness of cameras, proximity sensors, and night vision detectors during emergency vehicle driving, which may shed light on developing advanced strategies for preventing such crashes.

CONCLUSION

Differences in *personal factors* (e.g., individual physical differences, driver experience and training, driver behavior) are observed between emergency vehicle drivers and general motor vehicle users. Due to the strict screening, qualification, and training requirements of the emergency vehicle drivers, individual physical differences (e.g., age, gender) of responders played little role on incidents of emergency vehicles. However, overconfidence in driving among experienced emergency vehicle drivers has been reported as one of the contributing factors leading to adrenaline rush and dangerous behavior during ED, and the "code 3 running" thinking and drivers' risk tolerance on the road intensify risky driving attitudes and behaviors.

Emergency vehicle driving is characterized by a series of *task demands* (e.g., time pressure, secondary tasks, and use of lights and sirens) and irregular and unpredictable work circumstances (e.g., long shift hours and driving in stressful situations). Time pressure could push drivers into speeding and thus contributes to increasing cognitive demands, reducing the time available to stop or maneuver to avoid a crash; and elongating a dilemma zone, which may induce premature decision making during driving and at intersections. Secondary-task demands (e.g., finding maps, scanning sites, and communicating with dispatchers) during "code 3 running" may lead to driver distraction or eyes off the road during driving, which increases response time in maneuvering. Extensive use of lights and sirens could delude emergency vehicle drivers into a false sense of invincibility on the road, which leads to more aggressive and abnormal driving behaviors. Working under long shift hours is considered one of the contributing causes of fatigued and drowsy driving, which may not only delay drivers' reaction time but also reduce their visual efficiency. Furthermore, emergency vehicle drivers often drive at odd hours, in unfamiliar areas, and even during disasters. These stressful driving conditions influence their physical, mental, and emotional states, which may have negative impacts on their driving performance. Strategies to enforce safety policies and improve control measures to mitigate secondary-task workloads and augment decision-making capacities of emergency vehicle drivers are warranted.

Due to the *physical features of emergency vehicles* (e.g., upgraded engines, increased weight and size, high center of mass, and different acceleration/deceleration characteristic), sharing the road among emergency and general vehicles is a challenge to both emergency vehicle drivers and other road users. Large emergency vehicles (e.g., fire truck, ambulance) are generally tall and thus have a high center of mass, producing a larger lateral momentum during driving, which could impede the driver's maneuvering. In addition, the large and tall vehicles could occlude the vision of nearby road users. Moreover, heavy emergency vehicles have low acceleration and deceleration capabilities, requiring longer time and distance for the vehicles to gain speed or stop, which increase the length of dilemma zone and the number of chances for traffic conflicts with approaching vehicles at intersections. Finally, warning sirens and warning lights could limit emergency vehicle drivers' acquisition of auditory information and impede the vision of adjacent road users due to their loudness and glare. Efforts are warranted for improved policies and vehicle design standards to enhance emergency vehicle driver safety as well as public education to help public road users recognize the hazards when driving near emergency vehicles.

Emergency vehicle driver performance is influenced by various *environmental factors* (e.g., intersections, traffic rules, traffic signals, roadway designs, and weather conditions). Intersections typically contain multifaceted environmental factors and are the locations where emergency vehicles have had the most traffic conflicts. Heavy and large emergency vehicles (e.g., ambulance, fire apparatus) could aggravate the situations because the long length of the vehicles, low acceleration/deceleration capabilities, and high-speed driving behaviors during ED increases the length of dilemma zone, which makes it harder for nearby road users to predict and judge the actions of emergency vehicles. In addition, the current length of the yellow light phase is less than the optimal length for fire trucks and ambulances, which is an additional risk to emergency vehicle drivers. It is also worth noting that emergency vehicle crashes are reported to occur often at favorable environmental conditions (e.g., daytime, clear weather, dry road, and lower road speed limit). Aside from the fact that a large percentage of emergency vehicle driving takes place in such favorable environmental conditions, road users are desensitized and exercise less caution under the favorable environmental conditions. More creative strategies and technologies, such as vehicle-to-vehicle and vehicle-to-intersection smart communication technologies, may be warranted for mitigating the adverse impacts of the environmental factors on emergency vehicle safety on the road.

Finally, this article identified six knowledge gaps to be addressed for improving our understanding of the mechanism of emergency vehicle crashes and for developing strategies to proactively enhance emergency vehicle safety on the road. Among the gaps are emergency vehicle driver risky behavior mitigation, behavior carryover between emergency response and return from a call, distraction in emergency vehicle driving and in-vehicle driver assistance technologies, vehicle design and sirens, emergency vehicle red light running, and pedestrian crash control.

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KEY POINTS

- Differences in personal factors are observed between emergency vehicle drivers and general vehicle drivers. Time pressure, secondary-task demands (i.e., multitasking activities), long shift hours, and extensive use of lights and sirens are among notable risk factors for emergency vehicle crashes. Research on improved control measures, such as advanced driver assistance technologies, vehicle-to-infrastructure communication-enabled systems, and safety guidelines to augment decision-making capacities of emergency vehicle drivers, are warranted.
- Emergency vehicle driving requires special skills for drivers due to the unique features of the vehicles (e.g., upgraded engines, increased weight and size, high center of mass, and different acceleration/deceleration characteristics). The unique vehicle features could also adversely affect adjacent road users in various ways.
- Emergency vehicle driver performance is influenced by various environmental factors (e.g., intersections, traffic rules, traffic signals, roadway designs, and weather conditions). Intersections typically contain multifaceted environmental factors and are the locations where emergency vehicles have had the most traffic conflicts.
- A series of research concepts for reducing emergency vehicle crashes are offered for the human factors community to address, including emergency vehicle driver behavior carryover between emergency response and return from a call, distraction in emergency vehicle driving, emergency vehicle red light running, in-vehicle driver assistance technologies, and pedestrian crash control.

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