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Understanding the impacts of mobile phone distraction on driving performance: A systematic review

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Abstract

The use of mobile phones while driving—one of the most common driver distractions—has been a significant research interest during the most recent decade. While there has been a considerable amount research and excellent reviews on how mobile phone distractions influence various aspects of driving performance, the mechanisms by which the interactions with mobile phone affect driver performance is relatively unexamined. As such, the aim of this study is to examine the mechanisms involved with mobile phone distractions such as conversing, texting, and reading and the driving task, and subsequent outcomes. A novel human-machine framework is proposed to isolate the components and various interactions associated with mobile phone distracted driving. The proposed framework specifies the impacts of mobile phone distraction as an inter-related system of outcomes such as speed selection, lane deviations and crashes; human-car controls such as steering control and brake pedal use and human-environment interactions such as visual scanning and navigation. Eleven literature-review/meta-analyses papers and 62 recent research articles from 2005 to 2015 are critically reviewed and synthesised following a systematic classification scheme derived from the human-machine system framework. The analysis shows that while many studies have attempted to measure system outcomes or driving performance, research on how drivers interactively manage in-vehicle secondary tasks and adapt their driving behaviour while distracted is scant. A systematic approach may bolster efforts to examine comprehensively the performance of distracted drivers and their impact over the transportation system by considering all system components and interactions of drivers with mobile phones and vehicles. The proposed human-machine framework not only contributes to the literature on mobile phone distraction and safety, but also assists in identifying the research needs and promising strategies for mitigating mobile phone-related safety issues. Technology based countermeasures that can provide real-time feedback or alerts to drivers based on eye/head movements in conjunction with vehicle dynamics should be an important research direction.

Keywords:

Driving distraction

Mobile Phone

Human-machine interaction

Road Safety

Dual-Task

Systematic review

1. Introduction

Mobile phone distracted driving (MPDD) is an ongoing challenge for transport network managers. Observational studies conducted in the United States reveal that 31.4 % of drivers talk on phone and 16.6% text or dial (Huisingh et al., 2015). Hickman and Hanowski (2012) reported that about 2.2% of commercial motor vehicle drivers were observed using mobile phones while driving. In Australia about 5% of drivers use handheld mobile phones whilst driving (Young et al., 2010), 3.4% in the United Kingdom (Sullman et al., 2014), and 14.1% in Spain (Prat et al., 2015). In an epidemiological study in the United States, about 69% of drivers aged between 18–64 years reported having engaged in a mobile phone conversation at least once in the past month (Overton et al., 2014). Meanwhile, about 60.4% drivers in New Zealand reported being involved in mobile phone conversations in a typical week, about 66.2% read 1–5 text messages while driving, and about 52.3% sent 1–5 text messages while driving (Hallett et al., 2011, 2012). Similarly, in Portugal, about 28.5% of a web-based sample of drivers reported using a mobile phone at least once a day (Ferreira et al., 2013). A survey conducted in Australia reported that almost one in two Australian drivers aged between 18 and 24 years use handheld mobile phones while driving, nearly 60% of them send text messages, and about 20% of them read emails and navigate (AAMI, 2012). Brace et al. (2007) argued that mobile phone usage while driving will remain stable (or even increase) due to the high degree of integration of this technology into society, whether it is lawful or not.

Different studies report varying effects of MPDD on crash risk. An epidemiological study found that mobile phone conversations increase crash risk by a factor of four (Redelmeier and Tibshirani, 1997). Asbridge et al. (2013) reported that the odds of a culpable crash increase by 70% when the driver is using mobile phone. In the United States, an study of police crash reports showed that mobile phone distraction resulted in 18% of fatal crashes and 5% of injury crashes (Overton et al., 2014). Epidemiological studies and police reported data, however, often suffer from underreporting problems and do not record the exposure to mobile phone use, and therefore these estimates may be inaccurate. Experimental and/or naturalistic studies, on the other hand, are not suitable for estimating actual crash risk as crashes are rarely observed within the study design (Caird et al., 2008). Hence, the use of surrogate measures of safe driving performance has been common, but the variety of these measures and the irregular results obtained has impeded a better understanding of the risk of using mobile phones while driving (Caird et al., 2014a). Moreover, the nature of the relationship between surrogate measures and actual crash risk is poorly understood and evidence is lacking.

Surrogate measures for safety evaluation of MPDD often compare various driving performance metrics such as speed, lateral control and braking between baseline (no distraction) and distracted conditions. By observing these metrics, self-regulation of driving or mobile phone usage has been reported in naturalistic driving and simulator studies as a potential risk compensatory factor (Hickman and Hanowski, 2012). Yet, it remains unclear whether this phenomenon has implications on safety (Yannis et al., 2010). The behavioural alterations in driver behaviour, in response to changing external physical conditions, are often gauged in terms of speed selection (Reimer et al., 2014), response time to a mobile phone call (Tractinsky et al., 2013), deceleration and reaction time (Benedetto et al., 2012), following distance (Kass et al., 2010), use regulation (Hickman and Hanowski, 2012), stopping behaviour at the onset of yellow light (Haque et al., 2015), braking behaviour (Haque and Washington, 2014a) and reaction time (Haque and Washington, 2013, 2014b), among others.

The trend in literature has been to apply reductionist methodologies for analysing the impact of particular distractive conditions (i.e. dialling, texting, ringing, etc.) on driving performance. Results obtained from these studies may not be conclusive because they typically do not consider different distractive conditions simultaneously, leaving their combined effects on driving performance and safety largely unknown.

Knowledge of the underlying mechanisms of the human-machine system and their interactions is needed. The lack of this knowledge has hampered the formulation of more effective strategies for coping with MPDD (Young and Regan, 2008; Young and Salmon, 2012). More importantly, this information is vital for parameterization of driver behaviour and for the development of technology-based interventions and system architectures. It is therefore very important to develop an integrated framework that helps to identify how different distractive conditions lead to different driving performance and outcomes.

The relationship between MPDD and safety has fuelled a dialogue that includes psychological, medical, engineering, economic, political and social points of view. This dialogue has resulted in the total or partial ban of the use of mobile phones while driving in many places around the world. However, uncertainty remains about how mobile phone use independently or in association with other factors affects driving performance. This article proposes a systematic framework based on a human-machine system approach to identify all of the components and interactions of MPDD so the effects of mobile phone use can be systematically analysed.

The paper is organized as follows. The next section presents a new systemic approach for understanding the interactions among the driver, the car, and the mobile phone. Next, a research methodology and the search protocols for collecting relevant literature are discussed. This section is followed by a systematic analysis of the literature that is consistent with the proposed classification scheme. The paper concludes with a theoretical discussion on the appropriateness of the proposed model and highlights the research path moving forward.

2. Mobile phone distracted driving (MPDD) as a human-machine system

A systems approach is one of the most robust methods for analysing configurations with high structural complexity (Leveson, 2011). This robustness is enabled through the use of a line-base language for isolating system components and model relationships. In addition, the systems approach considers internal and external factors of the system arrangement, which allows identification and examination of the underlying assumptions of the model (Lederman, 1992). The combination of humans and technical systems is called a human-machine system (HMS) (Hastings, 2004). In a HMS, humans interact with technical systems at three levels: direct use, control, and supervision (Wieringa and Stassen, 1999). These interactions are accomplished by the use of controls and interfaces in the physical component, i.e. the plant of the technical system. The interfaces are the way in which the technical systems communicate visual, auditory or tactile information to the human user, while the controls are the means by which the human user operates the system (Cacciabue, 2004). In extended definitions, the HMS includes the working context, i.e. environment, other operators, collaborators, policies, rules, culture, and society; these are the so called Socio-Technical Systems (Cacciabue, 2004; Trist, 1981).

The novel paradigm proposed in this article defines MPDD as a HMS. Generally, a HMS includes observable interactions between humans and machines such as controlling the steering wheel or dialling a mobile phone (Degani, 1996). However, it must be acknowledged that humans also interact with technical systems using cognitive processes (e.g. decision-making process and cognition) (Reimer et al., 2012) that are not observable in the HMS and, therefore, were not modelled in this framework. Following the HMS approach, there are three main components in MPDD: the driver (i.e. human component), the plant (i.e. vehicle and mobile phone as two separate machines), and the environment (i.e. the road traffic environment). In a driver-car composite in normal driving conditions (without mobile phone use), humans interact with the technical system through direct use, control or supervision of the car. In MPDD, the mobile phone can be seen as a new independent technical system or machine that interacts with the driver, and thus increases the complexity of the HMS. The proposed HMS framework can accommodate variations within the components, including physiological and psychological variations among humans.

In order to analyse human-machine interactions, the components of MPDD are identified following a HMS model as shown in Figure 1. As marked in Figure 1(a), the components of the system are the driver, both plants (phone and vehicle), and the road traffic environment. Interfaces and controls are the basic mechanisms of a plant by which driver receives feedback from the machine and operates the machine, respectively. Variations in the system components can lead to fluctuations in in-vehicle tasks and associated system performance. Possible variations in the system components are summarized as follows:

(1) Driver (human component): Age, gender, driving experience, physical capabilities, trip purpose, decision-making process, and other demographic characteristics.

(2) Vehicle (plant component): Vehicle size, transmission type, vision through windscreen, etc.

(3) Mobile phone (plant component): Handheld, hands-free, touch-screen typing, voice command, keyboard interactions, etc.

(4) Road traffic environment (environment component): Motorway, urban roads, sub-urban roads, rural roads, intersections, weather, etc.

Following the principles of observable interactions between humans and machines in a HMS framework as suggested by Degani (1996), the proposed framework identifies five possible in-vehicle interactions in MPDD from the perspective of a HMS: human-car interface, human-car controls, human-mobile phone interface, human-mobile phone control, and human-environment interface (see Figure 1(b)). Each of these in-vehicle interactions has different tasks and associated performance measures; the details of these interactions are summarized in Table 1. For instance, talking on a mobile phone while driving is an in-vehicle task set in the human-mobile phone interface, which can eventually affect the system properties (described later) as well as the performance of the remaining four interactions. Additionally, some mobile phone tasks concurrently involve two interactions, in particular mobile phone control and mobile phone interface. For example, texting, and dialling using the tactile interface requires a driver to simultaneously use the mobile phone display and controls. This distinction is important for recognizing the complexity of the tasks, and the need for a driver to allocate additional resources when a concurrent interaction with control and interface takes place.

[Place Figure 1 about here]

The in-vehicle tasks shown in Figure 1(b) are comprised of two tasks: driving and using a mobile phone. These tasks can impact on each other; this causal influence can be described as 'interference between in-vehicle tasks'. The interference is a two-way interaction between the mobile phone task and the driving task. The typical approach in the literature has been to examine how the mobile phone task affects driving tasks such as navigation, response to road traffic events, brake pedal movements, and steering wheel controls. The inverse relationship—the influence of the driving task on secondary tasks like a mobile phone conversation, has also been reported in terms of changes in the performance of the secondary task while driving.

[Place Table 1 about here]

Together, changes in system components and interference between in-vehicle tasks have an impact on system outcomes. The main outcome of a HMS relates to its functional requirements or functionality. In the MPDD context, a system's functionality is related to mobility and is generally measured with parameters that describe the movement of the vehicle, such as acceleration, headway, lane position, and speed. In addition to functionality, the system outcomes have lifecycle system properties or "ilities" (De Weck et al., 2011). de Weck et al. (2012) have identified at least 15 lifecycle system properties including quality, reliability, flexibility safety, durability, resiliency, robustness and evolvability. Theoretically, every system should have all of these possible lifecycle system properties or ilities, and the same is true for MPDD. This study only reported five lifecycle systems properties (also called system properties as used in this paper) for MPDD as a HMS, as these were identified as a product of this review. Table 2 includes both the original and adapted definitions of these five system properties. Examples of system outcomes against each system property are also included in Table 2.

[Place Table 2 about here]

3. Methodology and research protocol

Applying the above HMS research lens to examine MPDD, a systematic literature review was conducted. Given the large amount of components and causal mechanisms theoretically described in the HMS, a systematic classification scheme (SCS) was developed to guide the literature review and to enable an assessment of the degree to which the current literature fits the proposed theoretical model (Anderson et al., 2011; Buelvas et al., 2013). Articles were searched in multiple data bases using a search strategy described in Section 3.2. Once the articles were collected they were reviewed and organised using the SCS.

The scope of this review was restricted to peer-reviewed journal articles as a control on the quality and rigour across different studies in the area of MPDD. The search strategy comprised of two separate steps: (1) investigating literature reviews/meta-analyses, and (2) analysing original research articles. A search was undertaken to identify literature reviews/meta-analyses on MPDD published in the 10 years 2005-2014. The last comprehensive literature review manuscript on the topic, that enabled the capture of prior research into the proposed MPDD framework of this study, was published by Collet et al. (Collet et al., 2010a, b). Therefore, the search for original research articles (i.e. not reviews/meta-analyses) was restricted to journal papers published between January 2010 and April 2015.

3.1. Systematic Classification Scheme (SCS)

The SCS is based on the integrative HMS framework developed for MPDD, which was adapted from the methodologies developed by Hachicha and Ghorbel (2012) and Lage Junior and Godinho Filho (2010). It includes a series of questions intended to summarise all HMS components and interactions considered in published articles on MPDD. In particular, the proposed classification scheme helped map the kinds of variation in HMS components, the types of interactions between humans and mobile phones, or of the different driving performance metrics that were used in earlier research. The methodological and technological parameters of the research approaches were also structured by the SCS, not only to generalize the research findings but also to identify limitations and future research directions. The SCS adopted in this study consists of the following six questions:

I. What was the study design (e.g. simulator studies, naturalistic studies)?

II. What variations in the HMS components (e.g. driver demographics, type of mobile phone use) were included?

III. What human-machine in-vehicle interactions (e.g. human-mobile phone interactions, human-car interactions) in MPDD were examined?

IV. What interference associations between in-vehicle tasks (e.g. changes in steering control due to a mobile phone task) were described?

V. What system performance metrics (e.g. speed, headway, lateral control) were utilized?

VI. What associations between in-vehicle interaction tasks and system performance metrics (e.g. effects of mobile phone conversations or texting on speed and lateral control) were considered?

3.2. Search strategy

All searches included the word “driving” as mandatory, followed by the terms “mobile phone”, “cell phone”, “cellular”, or “telephone”, and “distraction”, or “interruption”. These terms were sought in the full text of the manuscripts. Studies explaining the prevalence of MPDD from a social, legal, economic or psychological point of view, and proposals to intervene in the use of a mobile phone while driving, were excluded.

4. Research on mobile phone distracted driving

This section compiles research on MPDD collected from two types of studies: review/meta-analysis studies, and original research articles. Following the structure of the proposed SCS, section 4.1 systemically describes the findings from the past review studies and section 4.2 presents the findings from original research articles published between 2010 and April 2015.

4.1. A Synthesis of Literature reviews/meta-analyses published from 2005-2014

Several literature reviews/meta-analyses have studied the relationship between mobile phone distraction and road safety. From 2004 to April 2015, a total of 11 literature reviews/meta-analyses have been published. They included five literature reviews (Brace et al., 2007; Collet et al., 2010a, b; McCartt et al., 2006; Svenson and Patten, 2005), four meta-analyses (Caird et al., 2014a; Caird et al., 2014b; Caird et al., 2008; Horrey and Wickens, 2006), one systematic review (Ferdinand and Menachemi, 2014), and one review of state-of-knowledge (Ranney, 2008). The main characteristics of these articles are summarized in Table 3. The number of articles reviewed in these literature review/meta-analysis papers ranged from 5 to 165.

4.1.1. What was the study design?

As shown in Table 3, past literature reviews/meta-analyses have summarized findings from various types of studies including analysis of traffic crashes (Crash analysis), controlled on-road studies on a pre-set route with an instrumented car (Instrumented vehicle), observation of drivers in a uncontrolled road traffic environment (Naturalistic observation), simulation of specific in-vehicle task in a laboratory (Part-task simulation), simulated driving (Driving simulators), and use of self-reported data (Survey). Study designs are very important for analysing the impacts of MPDD on safety. Key advantages of driving simulator studies are: control of driving parameters (Svenson and Patten, 2005), economic feasibility (Brace et al., 2007), and safer conditions for the participants (Collet et al., 2010b) in contrast to naturalistic driving studies. However, driving simulator studies are often criticized for the lack of realism compared to real world driving where drivers can engage a variety of strategies such as pull over the vehicle to attend a secondary task (Caird et al., 2014b; Svenson and Patten, 2005). In addition, task driving conditions such as the use of uncommon conversations or verbalized simulator protocols often raise questions about the validity of findings in the area of MPDD and safety (Collet et al., 2010b). Although naturalistic studies are believed to have higher accuracy and validity (Caird et al., 2008), their small sample sizes often limit the generalization of findings (McCartt et al., 2006). Survey/epidemiological approaches, on the other hand, are subject to inherent bias due to underreporting and information loss.

Factors like data collection strategies, sample sizes, and tools of analysis are seldom examined in the literature reviews. A common practice has been to pool the studies based on the methodological approach without distinguishing the differences among data collection tools (Brace et al., 2007; Caird et al., 2014a; Caird et al., 2014b; Caird et al., 2008; Collet et al., 2010a, b; Ferdinand and Menachemi, 2014; Horrey and Wickens, 2006; McCartt et al., 2006; Ranney, 2008; Svenson and Patten, 2005). This may make the summarized results less reliable or comparable. Although Collet et al. (2010a); (Collet et al., 2010b) considered surveys and physiological measures as sources of information for summarizing the literature on MPDD, the technological differences and degrees of sophistication amongst studies were not discussed thoroughly. In addition to data collection strategies, the sample sizes of simulator studies and naturalistic driving studies are important and thus considered by many literature review studies on MPDD. McCartt et al. (2006) reported that the sample size ranged from 8 to 350 with a mean of 46 and median of 30 in driving simulator studies, a mean of 30 and median of 37 in on-road studies with instrumented vehicles, and a mean of 27 and median of 21 in naturalistic studies. To overcome the variability and limitations in sample sizes across research articles, meta-analyses are used to generalize findings on MPDD (Caird et al., 2014a; Caird et al., 2014b; Caird et al., 2008), but the tools used for data analysis have received less attention in summarizing the findings by the literature reviews/meta-analyses.

[Place Table 3 about here]

4.1.2. What variations in the HMS components were included?

Among the four components of the HMS in MPDD, the most studied are drivers and their demographics. Driver age has been reported to be inversely related to the ability required to share attention in a dual task execution like MPDD (Brace et al., 2007). However, as reported by McCartt et al. (2006), a lack of defined age ranges for young (approximately 16-25 years) and old (approximately 40-80 years) drivers coupled with unconsidered factors like driving experience, and mobile phone usage history often hinder deriving conclusive findings. The reported effects of driver gender on MPDD and safety have also been mixed (Brace et al., 2007; Collet et al., 2010b; McCartt et al., 2006).

Literature reviews of MPDD have not reported on the influence of vehicles—the plant component of the HMS. McCartt et al. (2006) considered vehicle transmission type as one of the variables for analysing the literature on MPDD and reported that it was often not specified in the studies. Svenson and Patten (2005) concluded that driving stress—measured as a function of the heart rate—of mobile phone distracted drivers increased by a lesser amount among drivers with automatic gearshift transmissions compared to manual gearshifts.

The effect of mobile phones, the second plant in the HMS, has been considered in many literature reviews mainly with a focus on whether hands-free technologies have less impact on the driving performances compared to handheld mobile phones. Most of the literature review studies have concluded that the crash risk of hands-free conversations is not significantly different from that of handheld phones (Brace et al., 2007; McCartt et al., 2006). Brace et al. (2007) and McCartt et al. (2006) concluded that handheld dialling leads to less safe driving as well as faster but inaccurate dialling of mobile phones. Horrey and Wickens (2006) and Caird et al. (2008) showed that the impairment of driving performance for a hands-free phone conversation is equivalent to that experienced as the result of an in-vehicle conversation. Svenson and Patten (2005) argued that the position of the mobile phone in the car could interfere with the in-vehicle tasks and needs to be investigated. The effects of other phone characteristics like the size and type of the mobile phone on MPDD are usually not available in the literature (McCartt et al., 2006).

The effects of road traffic environment on MPDD have been reported in a number of literature review studies (Collet et al., 2010a; McCartt et al., 2006; Svenson and Patten, 2005). These studies suggest that heavy traffic delays the execution of any secondary task in addition to decreasing the cognitive function of memory. However, there are discrepancies in findings about the impact of environmental complexity on MPDD (Brace et al., 2007).

4.1.3. What human-machine in-vehicle interactions in MPDD were studied?

As discussed previously, the proposed systematic framework for MPDD identified five possible in-vehicle interactions: human-car interface, human-car control, human-mobile phone interface, human-mobile phone control, and human-environment. Table 3 includes various in-vehicle interactions considered by literature review studies. Mobile phone conversation (an interaction in the human-mobile phone interface) and braking pattern (an interaction in the human-car controls) were the most studied in-vehicle interactions. Some studies have also analysed the effects of concurrent use of mobile phone control and interfaces like texting (Brace et al., 2007; Caird et al., 2014a; Caird et al., 2014b), answering (Svenson and Patten, 2005), dialling using the keyboard (Brace et al., 2007; Caird et al., 2014b; Collet et al., 2010a; McCartt et al., 2006), and navigation (Brace et al., 2007; Svenson and Patten, 2005) on MPDD. The simultaneous use of mobile phone controls and interfaces imposes a high workload on drivers and thus has been reported to represent a high risk situation. Although the effects of human-mobile phone interaction have been studied widely, the research on the varying effects of human-car interface interactions (e.g. reading the speedometer or odometer) on MPDD is relatively inexistent.

4.1.4. What interference associations among in-vehicle tasks were described?

The execution of any secondary task may have impacts on the performance of the primary driving task. The literature reviews and meta-analysis studies analysed how human-mobile interactions (secondary tasks) influence the primary driving task. The driving task was measured in terms of driver control of the car (human-car control) and driver reading of the road traffic situation (human-environment interaction). Table 4 summarizes the details of the effects of various human-mobile phone interactions on the 'human-car control' and 'human-environment' interactions. It appears that human-mobile phone interactions change the human-car control behaviour, leading to increases in both steering wheel corrections (Brace et al., 2007; Caird et al., 2014b; Collet et al., 2010a; McCartt et al., 2006; Svenson and Patten, 2005) and braking response times (Brace et al., 2007; Caird et al., 2014b; Caird et al., 2008; Collet et al., 2010a, b; Horrey and Wickens, 2006; McCartt et al., 2006; Ranney, 2008; Svenson and Patten, 2005). Mobile phone tasks were also reported to influence human-environment interactions, leading to a decrease in visual scanning of drivers. As seen in Table 3, the effects of secondary tasks on human-car interfaces were not addressed in the literature reviews.

[Place Table 4 about here]

4.1.5. What system performance metrics were utilized?

As reported in Table 3, the literature reviews/meta-analyses studies summarized the research findings on MPDD on a variety of system outcomes including functionality and various non-functional properties like occupancy, safety, and serviceability. *Functionality* was included in the form of speed selection, lateral position maintenance, and headway distance. *Occupancy* was measured in terms of driver's subjective workload, and *Safety* was measured in terms of the prevalence of crashes. *Serviceability* of MPDD was measured by drivers' memory utilization and information processing.

4.1.6. What associations between in-vehicle interaction tasks and system performance metrics were described?

Table 5 presents an analysis of the literature review studies to summarize the impact of various human-mobile phone interactions on system performance metrics. The impact of mobile phone conversation on system performance is the most studied topic in the literature review studies in contrast to other tasks, and has been reported to influence almost all of the system performance metrics including functionality (Brace et al., 2007; Caird et al., 2014b; Caird et al., 2008; Collet et al., 2010a; McCartt et al., 2006; Svenson and Patten, 2005), occupancy (Brace et al., 2007; Caird et al., 2008; Svenson and Patten, 2005), safety (Caird et al., 2014a; Caird et al., 2014b; Collet et al., 2010b; Ranney, 2008; Svenson and Patten, 2005), and serviceability (Collet et al., 2010b; Svenson and Patten, 2005). The analysis of the literature review articles suggested that conversing/dialling/texting while driving results in a reduction of driving speed but an increase in headways. However their effects on lane position are mixed.

As reported in Table 5, a consistent increase in driver's workload and decrease in memory and information processing were associated with different human-mobile phone tasks including interactions with mobile phone control, mobile phone interface, and concurrent interactions with control and interface. However, the effects of mobile phone tasks on crash involvement were not consistent across the literature review studies; some indicated an increase in crash involvement (Caird et al., 2014b), while others indicated negligible effects (McCartt et al., 2006).

[Place Table 5 about here]

4.2.Synthesis of literature from 2010-April 2015

Following the search strategy described in section 3.2, 62 journal articles were identified as being published on the topic of MPDD between January 2010 and April 2015. All 62 articles were critically reviewed and have been mapped onto the developed systematic classification scheme (SCS).

4.2.1. What was the study design?

Identified articles were categorized according to their study design, type of tool applied, and analytic method used to deduce the research findings (see Figure A1 in the appendix). Use of a driving simulator was the most implemented study design for investigating MPDD, accounting for about 63% of the studies on the topic. Simulator studies were more frequently conducted in custom built simulators or desktop simulators (61%) than high fidelity simulators (37%). Naturalistic studies represent 12% of the studies on MPDD, but about 63% of naturalistic studies were published in 2014-2015, representing a recent research effort in this area.

The sample size of a study, which influences the statistical power of analyses, generally depends on the type of study and experimental design. The average numbers of participants were 3043 in cohort studies, 1793 in naturalistic studies, 1248 in crash analyses, 56 in quasi-naturalistic studies, 46 in part-task simulations, and 39 in driving simulator studies. The analytical methods varied across the studies depending on the nature of the data and objectives. In particular, 44% of articles applied analysis of variance (ANOVA) to determine the differences between distracted and non-distracted driving performance and other parameters of interest. The study of MPDD has not generally been oriented to the analysis of complex interactions that require the use of modelling techniques and such studies are still scarce in the literature.

4.2.2. What variations in the HMS components were included?

Drivers were the most studied system component among the four components of the HMS in MPDD, as more than 84% of articles reported controlling for driver age or examining the effect of driver age on MPDD. In particular, about 11% of articles examined various performance differences under distracted driving across age groups, summarized in Table 6. Older drivers tend to engage less in a secondary task like using mobile phones while driving (Becic et al., 2010; Liu and Ou, 2011; Owens et al., 2011; Tractinsky et al., 2013). In contrast, the performance of younger drivers, who are inclined to use mobile phone while driving (Reimer et al., 2011), has been reported to be less affected by mobile phone tasks than older drivers (Asbridge et al., 2013). Many studies have also reported a negligible effect of age difference across various performance measures including speed selection (Reimer et al., 2011), stop sign pauses (Reimer et al., 2011), gaze behaviour (Reimer et al., 2012), driving task performances (Stavrinos et al., 2013), and risky driving behaviours (Zhao et al., 2013). Driver gender was also not a significant factor in many MPDD studies (e.g., Zhao et al. (2013)). The effects of driving experience on MPDD have been rarely studied. While Tractinsky et al. (2013) suggested that experienced drivers performed consistently better while driving under a secondary task, Stavrinos et al. (2013) did not find any effect of driving experience on MPDD.

A common assumption in the research is that different physical plants (i.e., handheld or hands-free mobile phones) may have an impact on driving performance (see Figure A2 in the appendix). It appears that nearly 41% of articles studied the effects of using hand-held devices on driving performances. An epidemiological study reported that the crash risk of using handheld phones is higher than using a hands-free technology (Backer-Grøndahl and Sagberg, 2011). Compared to hands-free phones, the use of a handheld phone while driving has been reported to influence various driving performances including an increase in braking response time, variations in headway, lateral lane position (He et al., 2014), and stopping behaviour (Haque and Washington, 2014a). Haque and Washington (2014b) and Benedetto et al. (2012), however, have not found any significant difference in reaction times between mobile phone modes. Soccolich et al. (2014) argued that hands-free technologies are more easy for conversing but less user-friendly for performing tasks like dialling and texting. Differences in the mobile phone input interfaces (i.e., touch screen vs. button style keyboard) have also been studied using driving simulators (McKeever et al., 2013; Reimer et al., 2014; Yannis et al., 2014; Young et al., 2014). Mobile phones with keyboard interface have been reported to have less impact on driving performance mainly because tactile pushbuttons require fewer glances off the road (Reimer et al., 2014).

[Place Table 6 about here]

The remaining two components are vehicle (plant) and road traffic environment (context). Differences in vehicles are underrepresented in the literature, and only one article to date has reported the effects of distraction for the drivers of commercial motor vehicles like heavy trucks and buses (Hickman and Hanowski, 2012).

The impact of road traffic environment on MPDD was studied using different traffic scenarios, roadway geometric features, and traffic characteristics (see Figure A2 in the appendix). The most common road environment scenarios were urban roads (46%), and driving along highways (43%). Most of the simulator scenarios (about 62%) included a two-lane road for studying MPDD. Other roadway, traffic and environmental factors included horizontal and vertical alignment (Tractinsky et al., 2013), traffic volume (Alosco et al., 2012; Stavrinos et al., 2013; Tractinsky et al., 2013), road works (Arnold and Houten, 2011; Dula et al., 2011; Platten et al., 2013), night time driving (Leung et al., 2012; Yannis et al., 2014), rainy condition (Yannis et al., 2014), and driving in tunnels (Rudin-Brown et al., 2013; Young et al., 2014). Under a complex driving environment with a narrower lane, high speed limit, and frequent presence of intersections and roadside buildings, drivers distracted by mobile phone conversations were reported to select a lower driving speed with higher variability and higher lateral acceleration (Liu and Ou, 2011). Demanding driving scenarios like driving along windy roads and driving in heavy traffic have been reported to influence driving speed and lane position variability of mobile phone distracted drivers (Tractinsky et al., 2013). Becic et al. (2010) reported that drivers under MPDD prioritize the driving task over the secondary task depending on the complexity (i.e., straight road segment or intersection) of the road traffic environment. The speech production of the drivers engaged in mobile phone conversations has been reported to decrease when the difficulty of driving increased (Becic et al., 2010). Tractinsky et al. (2013) found that driving along windy roads and heavy traffic resulted in a delayed response to attend incoming calls; additionally, in complex situations drivers showed less willingness to initiate or accept incoming phone calls. Similarly, Atchley and Chan (2011) argued that drivers using the mobile phone may increase their vigilance even when driving in a less stimulating environments. In summary, the complexity of road traffic environment appears to influence both the driving task and mobile phone tasks in MPDD. Overall, it can be observed from the reviewed articles the existence of a close relationship between the driving behaviour and environment; however, it must be acknowledged that the research does not cover the wide range of interactions present in the road traffic network.

4.2.3. What Human-machine in-vehicle interactions in MPDD were studied?

Following the human-machine framework of MPDD, topics covered in the research articles from 2010 to April 2015 were categorized into various human-car, human-mobile phone, and human-environment interactions (see Figure A3 in the appendix). Not surprisingly, distraction due to mobile phone conversations, a human-mobile phone interface interaction, has been a predominant topic in the recent literature being studied in about 60% of articles, followed by texting, an interaction that requires a concurrent use of mobile phone control and interface, which has been studied in about 38% of articles. About 24% of articles examined the human-environment interaction in the MPDD context but mainly focused on how distracted drivers capture visual environment information.

In contrast to interactions studied in the earlier literature reviews/meta-analyses, recent research has investigated some new human-mobile phone control and human-mobile phone interface interactions in MPDD. Recently studied human-mobile phone control interactions included how drivers handle the mobile phone while driving (Haddington and Rauniomaa, 2011), and recently studied human-mobile phone interface interactions included the effect of mobile phone ringing on driving performance (Holland and Rathod, 2013; Zajdel et al., 2013; Zajdel et al., 2012). Similar to the literature reviews/meta-analyses published from 2005-2014, the effects of human-mobile phone interaction have been studied widely but the effects of human-car interface interactions on system performance are in need of scholarly research.

4.2.4. *What interference associations among in-vehicle tasks were described?*

Interference is a two-way phenomenon in which both driving task and mobile phone task are perturbed. The research to date has mainly tended to focus on the impact of mobile phone tasks on the driving task. Mobile phone tasks have been reported to influence mainly human-car control and human-environment interactions, but a small amount of research is found on the effects of mobile phone use on human-car interface interactions.

Human-car control interactions in the context of MPDD have mainly been studied by examining steering patterns, speed maintenance and braking behaviour. Steering wheel corrections were higher among drivers distracted by a mobile phone (Zhao et al., 2013), particularly with conversations (Garrison and Williams, 2013) and texting (Owens et al., 2011). The ability to maintain a constant speed decreases significantly when a driver is texting (Choi et al., 2013); however, this result contradicts with other research that reported a negligible effect of mobile phone conversations on speed maintenance (Cao and Liu, 2013; Reimer et al., 2012) or distraction due to drivers preparing to attend an incoming call (Holland and Rathod, 2013). The braking task has also been reported to be affected by mobile phone tasks. In general, distracted drivers brake aggressively when approaching an obstacle (e.g. pedestrian crossing) along the road (Berg and Dessecker, 2013; Haque and Washington, 2014a). Compared to hands-free driving, drivers using a handheld phone tend to brake more frequently (Zhao et al., 2013). Interestingly, there is a consensus that braking time increases with the dual task demands, including conversing (Benedetto et al., 2012; Berg and Dessecker, 2013; Bergen et al., 2013; Kim et al., 2013; Long et al., 2012; Rossi et al., 2012), texting (He et al., 2014; Leung et al., 2012; Long et al., 2012), dialling (Platten et al., 2013), and ringing (Zajdel et al., 2013).

Human-environment interaction in the MPDD context has mainly been measured by examining eye behaviour (i.e., blink rate, gaze concentration, gaze position, etc.) as a proxy for capture of critical information from the surrounding road traffic environment under distraction. Drivers distracted by mobile phone conversations have been reported to have an increased gaze concentration, implying less peripheral awareness and detection sensitivity (Reimer et al., 2012). In particular, mobile phone distractions lead to a decrease in vertical and horizontal glances (Briggs et al., 2011; Reimer et al., 2012). Mobile phone tasks such as reaching, answering, dialling, texting, and browsing were found to be associated with longer off-road glances (Simons-Morton et al., 2014), with texting tasks requiring more frequent and longer off-road glances (Owens et al., 2011; Reimer et al., 2014; Tivesten and Dozza, 2014; Young et al., 2014) and emotionally involving mobile phone conversations leading to a pattern of visual tunnelling with a decline in visual fixations (Lansdown and Stephens, 2013). Eye behaviour alone may not be sufficient to truly understand the human-environment interaction in the MPDD context since eye behaviour may not give provide adequate information on the decision making process of drivers. Drivers distracted by mobile phone conversations have been reported to take a longer time to detect a pedestrian at a zebra crossing (Haque and Washington, 2014b), indicating not only impaired peripheral scanning behaviour but also a slow information processing ability. Garrison and Williams (2013) noted that distracted drivers put more attention to driving-relevant objects compared to less relevant objects like billboards, indicating a strategic decision by drivers to manage the human-environment interactions.

Apart from the influence of mobile phone tasks on driving performance, recent research also suggested a reverse effect—that is, the negative influence of driving task on mobile phone tasks. Becic et al. (2010) reported that performing dual tasks like driving while talking over a mobile phone influences both driving performance and conversation including quality loss in speech comprehension, language encoding and language production. Other effects on conversation include loss of quality in speech production, complexity (Atchley et al., 2011) and rhythm (Maciej et al., 2011). Cao and Liu (2013) reported that concurrent vehicle lane keeping and speech comprehension tasks did not affect lane keeping performance but the performance of a comprehension task was reduced. Spence et al. (2013) reported a loss of accuracy in conversation when distracted drivers were assigned a demanding cognitive task. Driving task has also been reported to influence texting performance with an increase in accuracy errors (Alosco et al., 2012) and response times (He et al., 2014).

4.2.5. What system performance metrics were utilized?

As for the analysis of the literature review/meta-analysis studies, the system performance metrics for MPDD were categorized as the parameters of the HMS described earlier in section 2. Figure 2 presents the distributions of articles from 2010-April 2015 according to system outcomes including functionality, occupancy, quality, resiliency, safety, and serviceability. While the primary parameter *functionality* of the HMS in the MPDD context refers to speed, acceleration, lane position, and headway, the non-primary function *occupancy* refers to the drivers' subjective workload; *quality* refers to navigation, and road edge excursions; *safety* refers to crashes, and other surrogate measures of safety like near misses and time-to-collisions; *serviceability* refers to drivers' memory utilization, and information processing ability; and *resiliency* refers to overtaking.

[Place Figure 2 about here]

4.2.6. What associations between in-vehicle interaction tasks and system's performance metrics were found?

Functionality: Recent literature has examined various functionality parameters of the HMS in the context of MPDD, including speed, acceleration, lane position, and headway distance. The speed selection of drivers has been reported to be influenced by various types of mobile phone tasks, including conversation (Becic et al., 2010; Metz et al., 2015; Reimer et al., 2011; Tractinsky et al., 2013; Yannis et al., 2010), holding a mobile phone (Christoph et al., 2013), navigation (Christoph et al., 2013), reading (Rudin-Brown et al., 2013), reaching to a mobile phone (Christoph et al., 2013), texting (McKeever et al., 2013; Thapa et al., 2014), answering by pressing the send button (Tractinsky et al., 2013), and dialling (Tractinsky et al., 2013). While a majority of studies reported a decrease in speed selection under MPDD, some reported an increase in speed for mobile phone conversation (Garrison and Williams, 2013; Liu and Ou, 2011; Stavrinos et al., 2013), and texting (Rudin-Brown et al., 2013; Young et al., 2014). Speed variability has been reported to increase if the conversation includes emotional components (Dula et al., 2011). A study matching self-reported behaviour and observed driving performance found that drivers who reported frequent use of a mobile phone while driving changed speed more rapidly with faster throttle accelerations, and sudden non-directional accelerations (Zhao et al., 2013). Platten et al. (2013) reported that distracted drivers approaching hazardous situations decreased speed rapidly with higher decelerations.

Distracted drivers have been reported to have less lane deviation while conversing (Garrison and Williams, 2013; Reimer et al., 2014) but an increased deviation while texting (McKeever et al., 2013; Rudin-Brown et al., 2013) compared to non-distracted drivers. Many studies, however, have reported a negligible difference in lane position between the baseline and the distractive conditions (Cao and Liu, 2013; Irwin et al., 2015; Young et al., 2014). In terms of headway maintenance, distracted drivers have been reported to maintain a longer following distance (Bergen et al., 2013; Yannis et al., 2010) and to have more gap variations (He et al., 2014). Pouyakian et al. (2013) reported that drivers answer mobile phone calls more frequently when headway distance is greater than 25 m.

Occupancy: System occupancy refers to the utilization of resources in the system, which is mostly measured by the workload of the drivers in the MPDD context. Various subjective or thorough physiological measures have been used to measure driver workload, including eye movement, skin conductance (Reimer et al., 2012), skin temperature, and heart rate (Chen, 2013). Drivers workload (demand) has generally been found to increase in all the dual task conditions related to MPDD (Soccolich et al., 2014). Several studies (Owens et al., 2011; Young et al., 2014) reported that drivers' subjective workload is much higher in a driving while texting condition compared to other mobile phone tasks. Long exposure to driving with mobile phone distraction has been reported to decrease the workload perceived by the driver (Arnold and Houten, 2011).

Quality: Quality of the HMS in the MPDD context refers to proficiency in mobility, which can be measured with travel time and traffic violations. Mobile phone conversation has been found to impair the quality of the system as drivers distracted by mobile phone conversations committed more driving errors and road violations, e.g. road lanes excursions, speeding, red light running (Nabatilan et al., 2012). In contrast, Dula et al. (2011) and Platten et al. (2013) have not found any significant difference in the number of traffic light infractions for conversation tasks.

Safety: About 24% of the articles published from 2010-April 2015 reported associations between MPDD and safety. Many epidemiological studies reported a strong causal link between crashes and the presence of a mobile phone in a car (Asbridge et al., 2013; Backer-Grøndahl and Sagberg, 2011; Farmer et al., 2010; Tivesten and Dozza, 2014). On the other hand, a decrease in crash risk due to mobile phone manipulation has been argued to be the effect of learning-adaptation of drivers (Backer-Grøndahl and Sagberg, 2011; Petzoldt et al., 2014). Farmer et al. (2010) also argued that there is no evidence as yet that the ban on mobile phones decreased crash rates in the United States. However, epidemiological approaches of this kind have some limitations such as under-reporting and misjudgement of the mobile phone exposure, and hence the results should be considered with due care (Asbridge et al., 2013).

Empirical studies, in contrast, do not include high number of crashes and thus usually do not report on crash risks associated with MPDD. Among the few studies that have discussed safety, mobile phone tasks like dialling (Tractinsky et al., 2013), and texting (Alosco et al., 2012; Bendak, 2014; Kim et al., 2013; Stavrinos et al., 2013) have been reported to increase the frequency of collisions. Activities that require drivers to take their eyes off the road result in a higher likelihood of crashes (Hickman and Hanowski, 2012); the longer the off-road glance, the higher the resultant crash risk (Simons-Morton et al., 2014).

Serviceability: The serviceability of MPDD includes the cognitive function of drivers required for performing various tasks including driving and using mobile phones. The literature analysing this support function has been mainly focused on memory utilization and the information processing capability of drivers distracted by mobile phones. Research has shown that language production and comprehension capability, measured as the accuracy of drivers storytelling task, decreases in the MPDD condition (Atchley et al., 2011). Conversation performance like the encoding of products of comprehension into memory is also relatively more affected when a person is involved in driving (Becic et al., 2010).

Resiliency: The overtaking manoeuver, a measure of resiliency which refers to how the system improves proficiency loss due to mobile phone distraction, was reported in one study in the recent literature. Stavrinos et al. (2013) reported that there was no significant association between distraction (mobile phone conversations or reading text messages) and cars the distracted drivers passed in a simulated network. However, there is a paucity of research whether or how a distracted driver performs an overtaking manoeuver.

5. Discussion and future research directions

This paper presents a novel systematic framework based on HMS with the intent to provide an in-depth and comprehensive understanding of the components and mechanism of MPDD. Although an understanding of the mediating factors is important for the effective design of countermeasures and for understanding the differences in driver populations, little research on these has been conducted (Young and Regan, 2008). The ultimate aim of defining MPDD using the HMS framework is to properly understand how differences in the components affect the system and interactions between tasks and the system performance outcomes in order to identify where on the system breaches in performance are occurring, and how interventions and strategies can serve to improve safety.

At a more detailed level, the proposed approach helps explain how system components and their interactions affect in-vehicle tasks in the interface or controls of vehicle and the mobile phone in combination with road traffic environments. This explanation involves dividing in-vehicle tasks into sub or smaller tasks according to the use of the interfaces and controls, which make it possible to explain the complexities involved with these activities. For example, texting and driving, which requires a simultaneous use of mobile phone controls and interfaces by drivers, is a complex task.

The proposed framework also describes how dual in-vehicle tasks affect both driving and mobile phone task performance. Subsequently, the model explains how in-vehicle tasks affect road traffic system properties adapted from system lifecycle properties defined by de Weck et al. (2012). The road traffic system properties include functionality, safety, serviceability, occupancy, quality and resiliency. The inclusion of system properties brings theoretical clarity on how MPDD affects various road traffic system properties, and identifies the research gaps, common issues and research needs in the area of MPDD. However, most of the studies that resulted from following the methodology studied behavioural issues on MPDD. This shows a lack of knowledge on these systemic interactions which potentially undermine efforts of practitioners and decision makers for understanding the impact of MPDD and designing robust countermeasures.

Research design: Driving simulator and naturalistic studies are common approaches to examine MPDD. In the literature, it has been argued that simulator studies still need to overcome their limitations in terms of ecological validity and driver engagement (Leung et al., 2012; McCartt et al., 2006). Despite these limitations, they will continue to be used mainly because of ethical and safety issues. However, many simulator studies in the area of MPDD have applied a reductionist methodology to examine the effects of a particular type of distraction (e.g., mobile phone conversation, texting, etc.) on driving performance. It is still not well understood how drivers manage in-vehicle secondary tasks and, not having this information on driver behavioural models may over- or underestimate the impact of MPDD. A simulator experiment could be useful to investigate when and how a driver engages in a secondary task like using a mobile phone while driving (strategic behavioural adaptation), and how they manage or compensate for the risk of distracted driving (operative and tactical behavioural adaptation), and the resultant effects on overall system performance. The measurement of different levels of behavioural adaptation could be employed for calibration of traffic behavioural models in order to measure its effect on system performance and supporting mobile phone-vehicle cooperation technologies that could potentially prevent unsafe risk compensatory strategies.

Advancements in technological capabilities for data collection and analysis have led to an increased number of naturalistic studies since 2010. Naturalistic studies address the limitation of simulator studies in terms of ecological validity and driver engagement and are likely to bring insights into the consequences of MPDD. However, they do not expose participants to the same road traffic situation or distractions. At the moment, the relative validity of simulator studies compared to on-road studies is unknown (Collet et al., 2010b), and remains an interesting topic for future research—the answer to which may assist researchers to better design a research methodology to understand the influence of MPDD on driving.

Small samples sizes and population bias are two common issues in the MPDD literature. The average sample size among articles published between 2010-2014 was about 39.4, whereas the average sample size among studies prior to 2010 was about 30.0 (McCartt et al., 2006)—suggesting that more recent efforts have tried to obtain larger samples. A future study focussing on the sensitivity of sample sizes may help researchers to determine optimal sample sizes for their research designs. Another point of contention is potential population bias in research design. As argued by Alosco et al. (2012), the research findings on distracted driving could be different if the participants were not "healthy young adults". It is a common belief that driving distraction effects are likely to be different across individuals depending on their cognitive capacity, driving exposure, health condition and various human behaviour factors like sensation seeking and aggressiveness. While there is much potential for research in this area, an emerging and related research need is to examine how vocational drivers like ambulance drivers, policemen, and taxi drivers manage in-vehicle communication tasks while driving, given that these driver groups are regularly exposed to distracted driving within their job responsibilities.

HMS components: Among the three components of MPDD, the most studied components are drivers and their demographics. The effects of driver age and gender on MPDD are mixed, but the experience of distracted driving may play a major role in maintaining a proficient performance while driving (Asbridge et al., 2013; Tractinsky et al., 2013). The safety implications of these findings are enormous. For instance, intelligent support systems able to detect distracted driving based on control parameters may fail to detect this particular group of experienced subjects. In order to increase the robustness of distraction detection systems, future research should focus on enhancing systems architectures through physiological and neural responses to distraction.

With regard to the modifications in the plant (i.e. mobile phone, car) of the proposed HMS, different types of mobile phone use have been studied in the literature. The most studied research question is whether hands-free driving is safer than driving with a handheld phone. It is reported that both types of mobile phone use have similar crash risk compared to baseline or non-distracted driving (Brace et al., 2007; McCartt et al., 2006; Soccolich et al., 2014). This result implies that the utilization of cognitive resources by drivers is the most important factor in the performance of driving tasks. The change in the mobile phone interface from keyboards to touch-screens has been reported to lengthen the off-road glances of drivers (Reimer et al., 2014), which may eventually increase the crash risk of distracted driving (Simons-Morton et al., 2014). Although various forms of mobile phone use have been studied, relatively little is known about how various vehicle features like steering control, manual/automatic gearshift, speedometer and other displays interact with mobile phone use and subsequent driving performance under the MPDD condition. Thus, the potential conflicts between mobile phone usage and vehicle features would be a worthwhile research pursuit. Potential technological advances could involve re-design of vehicle or mobile phone HMS plant to diminish potential conflicts. The road traffic environment plays a major role in MPDD (Fitch et al., 2014), but its effects have not been well studied, as the main focus of the majority of studies has been to examine the performance of distracted drivers across road traffic environments such as rural roads, highways, and urban roads. There remains a research gap in understanding how different road traffic scenarios impact vehicle control under distracted driving conditions. A lack of consistent definitions of traffic environment complexity has led researchers to consider the complexity of the road traffic environment intuitively. A theory-based approach could be used to define road traffic environment complexity and avoid overrepresentation of low probability events and complex manoeuvres. This may also help researchers to design better scenarios for the driving simulator to investigate how environmental complexity modifies the driving performance of distracted drivers and motivates their decisions to engage in distracting tasks like mobile phone conversations and texting. These results could also be used to create a more efficient and safer cooperative driving environment, since responses to mobile phone distracted driving could be calibrated on an environment-situation basis.

In-vehicle tasks: In-vehicle tasks examined include braking pedal and steering wheel control. Yet, other interactions such as accelerator pedal control and information procurement from the car interface appear to have been largely neglected in the literature. For instance, reading the vehicle speed from speedometer plays an important role in vehicle safety. If a direct impact on this task is found, research is needed on the design of safer vehicle interfaces including distraction as one of the design variables. Further research should include possible interference between driver-car interface tasks and mobile phone use. The lack of knowledge regarding these interactions prevents us from understanding their impact on driving performance and developing technology-based countermeasures (e.g., a real-time distraction monitoring system based on vehicle dynamics and eye/head movements of distracted drivers).

In contrast, in-vehicle mobile phone tasks include a large typology such as texting, conversing, navigating, and answering, among many others. Until now, the focus has mainly been on the conversation task; however, activities like conversing require the execution of other supporting tasks including dialling, answering, monitoring the battery and reaching for the phone. Research in this area must be able to consider these elements to provide a more realistic representation of the extent of MPDD. Another interesting opportunity for research is to understand the effects of ringing, navigation and dialling tasks.

In-vehicle tasks interference: The execution of in-vehicle tasks results in a two-way interaction between driving and using mobile phones. For instance, texting and conversations affect drivers car control including slower speed selection (acceleration pedals), variability in lateral position (steering wheel), and increased braking times. Simultaneously, MPDD influences the performance of mobile phone tasks as evidenced by language production rates and less accurate cognitive processing. Some researchers have suggested that this phenomenon may represent risk compensation behaviour of distracted drivers (Becic et al., 2010; Tractinsky et al., 2013). However, a well-designed experiment is needed to isolate each of these interference components so that the risk compensation of drivers may be traced and evaluated. This would allow development of a holistic model to explain distracted driving and help in finding technological solutions to minimize interference with driving tasks.

System performance metrics: The proposed system performance metrics allow measuring the impact of MPDD on the traffic system comprehensively. It is quite evident that MPDD does not only influence safety but also mobility in terms of quality and resiliency, implying that the performance of distracted drivers is impaired and they commit more driving errors and road violations. In addition, mobile phone distractions also decrease the cognitive function of drivers and distracted drivers often perceive higher levels of workload, which are respectively related to the system serviceability and occupancy. This review shows that most of the research has been focused on safety and functionality although MPDD has consequences on other system properties (e.g., serviceability, occupancy, etc.) as demonstrated by the findings of this study. There is a clear need for fundamental research to develop a comprehensive model that takes into account all system properties and quantifies the effect of MPDD on system performance metrics.

Associations between in-vehicle tasks and system performance metrics: Most of the relationships between in-vehicle tasks and the outcomes of the traffic system remain unclear in the literature. The most studied systemic outcome is functionality. So far, the majority of results show a significant decrease in speed while conversing on a mobile phone but this result was not as robust as it was for texting. In other functionality measures, lane position and headway have often led to conflicting results about the direction of the effect, but there is a difference between non-distracted and distracted conditions.

The bulk of the literature has so far offered conflicting and inconsistent results concerning the causal relationship between mobile phone distracted driving and system safety. Functionality parameters have been used as alternative indicator of safety of MPDD, yet this approach needs to be investigated in depth since the causal associations, if they exist, remain undefined (Becic et al., 2010). Recent naturalistic studies have not found changes in the crash likelihood in the conversation activity (Fitch et al., 2014; Hickman and Hanowski, 2012), while the opposite happens with texting and in general all in-vehicle tasks that require longer off-road glances (Simons-Morton et al., 2014). These data must be interpreted with caution, because naturalistic studies have restrictions in identifying the actual interactions with the road traffic environment and drivers moods (Metz et al., 2015). In contrast, while a strong causal association between texting and crashes has been reported, the results have not been consistent for conversations. Undoubtedly, longer off-road glances due to using the interfaces and controls of mobile phones play a vital role. In addition, more demanding texting tasks seem to have a greater impact on system safety, and specifically on the prevalence of collisions. Similarly, all activities that require drivers to take their eyes off the road result in higher likelihood of crashes (Hickman and Hanowski, 2012); the longer the off-road glance, the higher the resulting crash risk (Alosco et al., 2012; Simons-Morton et al., 2014). Technology-based countermeasures to provide real-time feedback based on eye behaviour could be a solid countermeasure for MPDD.

6. Conclusions

This study describes the mechanisms in which mobile phone interaction affects the driving task and system performance. To the authors' knowledge, this is the first attempt in which a systemic approach has been developed for synthesizing the literature on mobile phone distracted driving. The results provide an understanding of the empirical relationships observed in the MPDD literature—a literature that is full of controversial and divergent results. In this paper, a total of 75 documents were reviewed, covering literature reviews, meta-analysis and original research articles over a time span of 10 years.

Overall, the results of this study provide significant insight into the four fundamental issues surrounding MPDD. Firstly, it provides a framework that lists system components and defines their complex associations. However, it must be acknowledged that variations of the MPDD as a HMS can be found in real life applications, for example, presence of passengers in the car who may support the driver in using the mobile phone. These variations could be included in the HMS as new components and their interaction can be modelled. Secondly, it creates a system framework that allows for conceptual organization and prioritization of a variety of different performance indicators used in the literature on MPDD. Thirdly, it explains the phenomenon of compensation and helps identify its components in the MPDD model. Finally, it summarizes the current state of scientific progress in this research area and provides a map for future research.

In summary, a systematic framework that considers all of the components and interactions associated with MPDD will help to explain the risk compensation behaviour of drivers. It will accommodate the potential endogeneity within the relationship, and will enable greater insights than have been afforded to date. Our future efforts shall focus on implementing this analysis framework to achieve these aims.

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List of Figures

List of Figures in the Appendix

Figure 1. (a) Mobile Phone distracted driving as a HMS. (b) Causal mechanisms of the mobile Phone distracted driving as a HMS.

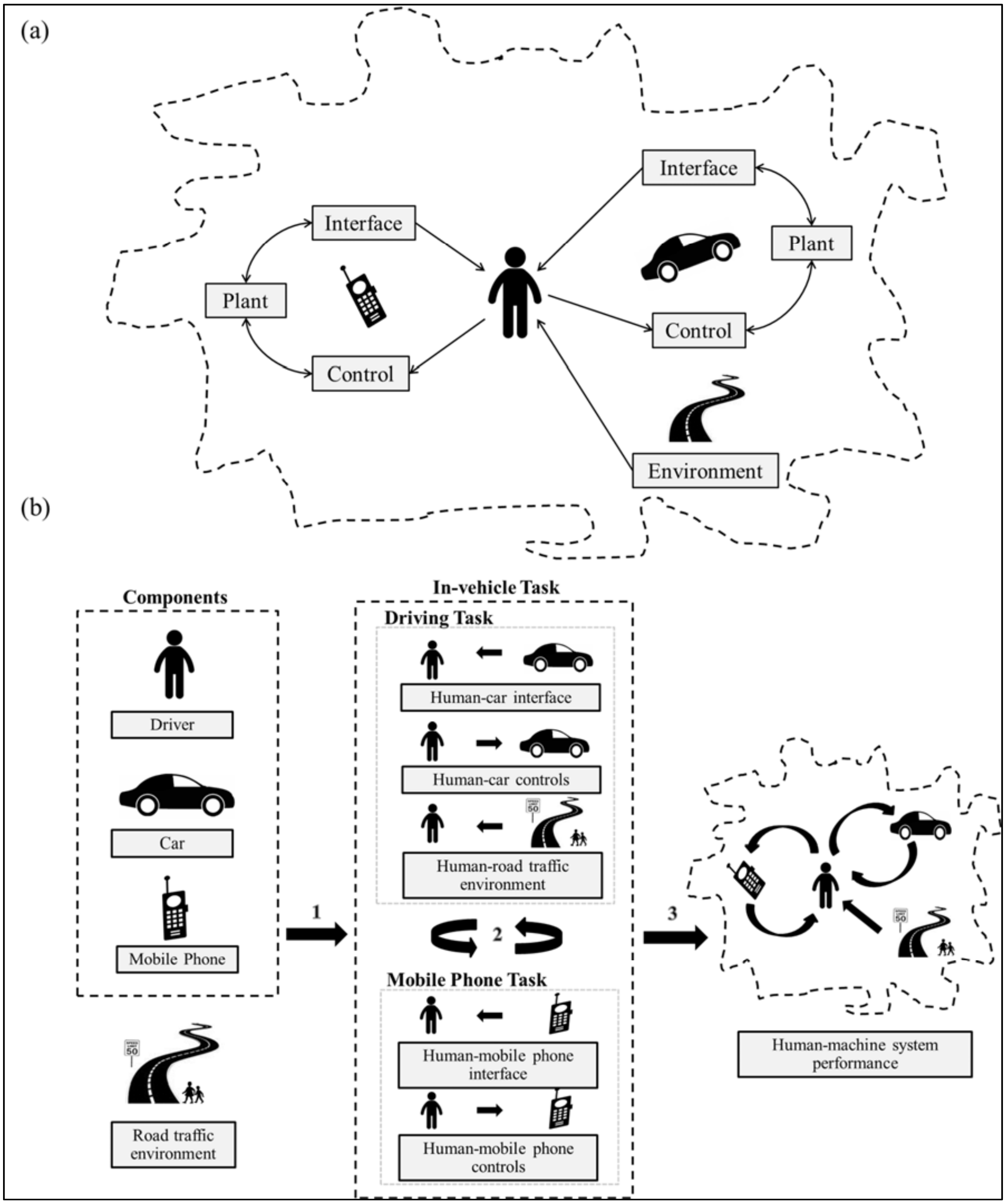
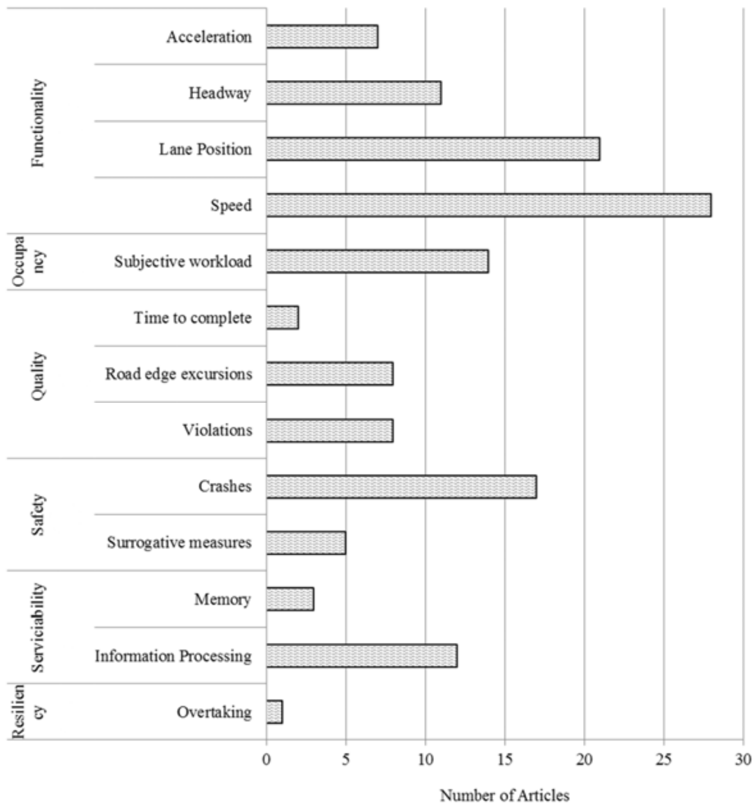


Figure 2. Distribution of articles according to system outcomes



List of Tables

Table 1. Definition and tasks of in-vehicle interactions

In-vehicle Interaction	Definition	Tasks
Driving task		
Human-car interface	Procurement of information from the car to the driver.	• Reading dashboard
Human-car controls	Usage of car’s control mechanisms by the driver.	• Steering wheel • Braking
Human-environment interface	Road traffic environment information appropriation for driving task execution.	• Capturing visual environmental information • Judging headway
Mobile phone task		
Human-mobile phone interface	Transmission of information from the mobile phone to the driver.	• Conversing • Ringing
Human-mobile phone control	Usage of mobile phone’s control mechanisms by the driver.	• Answering using voice interface • Dialling using voice interface • Handling • Reaching
Concurrent use of controls and interfaces	Usage of mobile phone’s control and interface mechanisms by the driver.	• Answering using tactile interface • Dialling using tactile interface • Browsing • Texting • Typing

Table 2. Systems properties in MPDD

System property	Definitions[†]	MPDD adaptations	Outcomes
Safety	Ability of the system to be free from accidents or unacceptable losses	Ability of MPDD as a HMS to be free from road trauma or property damage	• Crashes[‡] • Near-misses[‡] • Injury severity
Occupancy	Ability of the system to utilize its capacity	Ability of MPDD as a HMS to utilize capacity of driver, mobile phone and/or vehicle	• Driver workload[‡] • Mobile phone workload • Vehicle workload
Quality	Ability of the system to deliver requirements at a "high" level	Ability of MPDD as a HMS to meet the road rules, accomplishes travel plans, and delivers high-quality mobile phone service.	• Lane departures[‡] • Traffic violations[‡] • Travel time[‡] • Voice quality • Internet connection quality
Serviceability	Ability of the system to support its deployment	Ability of MPDD as a HMS to support mobile phone tasks engagement and performance.	• Memory[‡] • Information processing[‡] • Response time to mobile phone feedback
Resiliency	Ability of the system to return to its original function and performance following a disturbance or shock	Ability of MPDD as a HMS to return to its original function and performance following a disturbance or shock	• Overtaking for recovering speed[‡] •Time to recover targeted speed

[†] These definitions were adapted from those used in previously published studies of the Engineering Systems Division, Massachusetts Institute of Technology (Allen et al., 2002; De Weck et al., 2011; de Weck et al., 2012; Ross, 2014; Ross et al., 2011)

‡ These outcomes were found in the either literature reviews/meta-analyses (2005-2014) or Original research papers (2010-April 2015)

Table 3. Characteristics of literature reviews/meta-analyses reviewed

Author:	Svenson and Patten (2005)	McCartt et al. (2006)	Horrey and Wickens (2006)	Brace et al. (2007)	Caird et al. (2008)	Ranney (2008)	Collet et al. (2010a)	Collet et al. (2010b)	Caird et al. (2014a)	Caird et al. (2014b)	Ferdinand and Menachemi (2014)
Articles reviewed	78	125	23	65	33	5†	79	82	40	41	165
Type of studies analysed											
Crash analysis	x	x	-	-	-	-	x	x	-	-	-
Instrumented vehicle	x	x	x	x	x	x	x	x	x	x	-
Naturalistic observation	x	x	-	x	-	x	x	x	x	-	x
Part-task simulation	x	-	x	-	x	-	x	x	x	x	-
Driving simulation	x	x	x	x	x	x	x	x	x	x	x
Survey	x	x	-	-	-	-	x	x	-	-	-
HMS in-vehicle tasks											
Human-Car controls											
Braking	x	x	x	x	x	x	x	x	-	x	-
Steering wheel	x	x	-	-	-	-	-	-	-	-	-
Human-Environment											
Capturing visual environmental information	x	x	x	x	-	-	x	x	-	x	-
Judging headway	x	-	-	-	-	-	-	-	-	-	-
Human-Mobile phone Interface											
Conversing	x	x	x	x	x	x	x	x	x	-	-
Human-Mobile phone control											
Answering‡	x	-	-	-	-	-	-	-	-	-	-
Dialling‡	-	x	-	x	-	-	x	-	x	-	-
Reaching	x	-	-	-	-	-	-	-	-	-	-
Concurrent use of mobile phone control and interface											
Answering‡	x	-	-	-	-	-	-	-	-	-	-
Dialling‡	-	x	-	x	-	-	x	-	x	-	-
Browsing	x	-	-	x	-	-	-	-	-	-	-
Reading	-	-	-	-	-	-	-	-	-	x	-
Texting	-	-	-	x	-	-	-	-	x	x	-
Typing	-	-	-	-	-	-	-	-	-	x	-
HMS performance metrics											
Functionality											
Headway	x	-	-	x	x	-	x	-	-	x	-
Lateral Position	x	x	x	x	x	-	x	-	-	x	-
Speed	x	x	-	x	-	-	x	-	-	x	-
Safety											
Crashes	x	-	-	-	-	x	x	x	x	x	-
Occupancy											
Workload	x	-	-	x	x	-	-	-	-	-	-
Serviceability											
Information Processing	-	-	x	-	-	-	-	x	-	-	-
Memory	x	-	-	-	-	-	-	-	-	-	-

† Only includes literature review articles.

‡ This task can use voice or visual/tactile interfaces.

Table 4. Interference between in-vehicle tasks found in literature review/meta-analysis papers

	Human-car control		**Human-environment**	
	Steering Wheel	Braking	Visual Scanning	Judging Headway
Human-mobile phone interface				
Conversing	***Increase in movement amplitude:*** Collet et al. (2010a); McCartt et al. (2006); Svenson and Patten (2005)	***Increase in response time:*** Brace et al. (2007); Caird et al. (2008); Collet et al. (2010a, b); Horrey and Wickens (2006); McCartt et al. (2006); Ranney (2008); Svenson and Patten (2005)	***Decrease in visual scanning:*** Brace et al. (2007); Collet et al. (2010a, b); Horrey and Wickens (2006); McCartt et al. (2006); Svenson and Patten (2005)	N/D
Human-mobile phone control				
Dialling	***Increase in movement amplitude:*** Brace et al. (2007); Collet et al. (2010a)	***Increase in response time:*** Brace et al. (2007); Collet et al. (2010a)	***Decrease in visual scanning:*** Collet et al. (2010a); McCartt et al. (2006); Svenson and Patten (2005)	***Shorter judgements:*** Svenson and Patten (2005)
Concurrent use of mobile phone control and interface				
Navigating	N/D	***Increase in response time:*** Brace et al. (2007).	N/D	N/D
Texting	***Increase in movement amplitude:*** Caird et al. (2014b).	***Increase in response time:*** Caird et al. (2014b).	***Decrease in visual scanning:*** Caird et al. (2014b).	N/D

Table 5. Interactions between in-vehicle tasks and system outcomes found in literature review/meta-analysis papers

	Functionality			**Occupancy**	**Safety**	**Serviceability**	
	Speed	Lane position deviations	Headway	Workload	Crashes	Information Processing	Memory
Human-mobile phone Interface							
Conversing	***Decrease in driving speed:*** Brace et al. (2007); Caird et al. (2008); Collet et al. (2010a); McCartt et al. (2006); Svenson and Patten (2005)	***Increase in lane position deviations:*** Brace et al. (2007); McCartt et al. (2006); Svenson and Patten (2005) ***No change in lane position deviations:*** Caird et al. (2008); Collet et al. (2010a); Horrey and Wickens (2006)	***Increase in headway distance:*** Collet et al. (2010a); Svenson and Patten (2005) ***No change in headway distance:*** Caird et al. (2008).	***Increase in perceived workload:*** Brace et al. (2007); Caird et al. (2008); Svenson and Patten (2005)	***Increase in the number of crashes:*** Caird et al. (2014a); Ranney (2008); Svenson and Patten (2005) ***No change in the number of crashes:*** Collet et al. (2010B); Svenson and Patten (2005)	***Decrease in Information Processing:*** Collet et al. (2010b).	***Decrease in memory:*** Svenson and Patten (2005)
Human-mobile phone control							
Dialling	***Decrease in driving speed:*** Collet et al. (2010a); McCartt et al. (2006)	***Increase in lane position deviations:*** Collet et al. (2010a); McCartt et al. (2006)	N/D-	N/D	***Increase in the number of crashes:*** Caird et al. (2014a).	***Decrease in Information Processing:*** Collet et al. (2010b).	N/D
Answering	N/D	N/D	N/D	***Increase in perceived workload:*** Svenson and Patten (2005)	N/D	N/D	N/D
Concurrent use of mobile phone control and interface							
Navigating	N/D	N/D	N/D	***Increase in perceived workload:*** Svenson and Patten (2005)	N/D	N/D	N/D
Texting	***No change in driving speed:*** Brace et al. (2007); Caird et al. (2014b)	***Increase in lane position deviations:*** Brace et al. (2007); Caird et al. (2014b)	***Increase in headway distance:*** Brace et al. (2007); Caird et al. (2014b)	N/D	***Increase in the number of crashes:*** Caird et al. (2014a); Caird et al. (2014b)	N/D	N/D

Table 6. Summary of the articles studied the impact of age differences on the distracted driving

Author	Data/Research context	Age Groups	Results
Becic et al. (2010)	Simulation study: about 48 participants drove a high fidelity simulator; the driving scenario included an urban environment; the participants were engaged in mobile phone conversations while driving.	Young adult drivers: 19.6 years (1.4) Older drivers: 70.7 years (7.05)	Older drivers' speed was less variable under dual-task conditions compared to younger drivers. Older drivers performed poorly in the speech tasks.
Liu and Ou (2011)	Simulation study: about 48 participants drove a high fidelity simulator; the impact of hands-free phone conversation was studied for low and high cognitive loads	Young adult drivers: 23.1 years (1.54) Older drivers: 69.2 years (3.05)	Older drivers reduced speed and increased lateral deviation while using a hands-free mobile phone. Only complex conversations had an effect on younger drivers; however the change was not comparable with performance of older drivers.
Owens et al. (2011)	Quasi-naturalistic study: about 20 participants drove an instrumented car along a highway in the U.S. while texting using a mobile phone	Young adult drivers: 19 - 34 years Older drivers: 39 – 51 years	Older drivers took more time in the handheld texting task and made longer interior glances. The secondary task degraded the car control of older drivers to a greater extent.
Reimer et al. (2011)	Simulation study: about 37 participants drove a custom-built simulator; the driving scenario included an urban environment; participants were conversing with a hands-free phone	Young adult drivers: 15 - 25 years Older drivers: more than 50 years	No differences were reported among age groups in terms of speed. Heart rate only increased among young drivers. Young drivers tended to assign priority to attending to a mobile phone call and waited longer time in stop signs.
Reimer et al. (2012)	Quasi-naturalistic study: about 108 participants drove an instrumented car along a highway in the U.S. while performing a cognitive task.	Young adult drivers: 24.6 years (2.7) Middle aged drivers: 44.5 years (3.0) Older drivers: 63.3 years (3.1)	Participants in all age groups remained engaged in the secondary task despite its complexity. No differences in horizontal gaze concentration across the age groups.
Stavrinos et al. (2013)	Simulation study: about 75 participants drove a custom-built driving simulator; the driving scenario included a highway with three levels of traffic; participants were texting and conversing while driving.	Young drivers: 17.67 years (1.18) Young Adults drivers: 23.39 years (1.81)	The use a mobile phone while driving affected traffic flow irrespective of age. Young adult drivers experience was not a protective factor. No significant differences were found between age groups.
Tractinsky et al. (2013)	Simulation study: about 38 participants drove a high fidelity simulator; the driving scenario included two and four-lane straight roads; drivers responded and initiated calls using a hands-free phone.	Young drivers: 18 years (0.44) Young adult drivers: 26.4 years (1.92) Older drivers: More than 65 years	Young drivers were more likely to initiate calls; they did not manage the dual tasks at a strategic level and were less sensitive to road complexity. Elderly drivers had higher speed differences in heavy traffic. Older drivers had higher variance in lane position during conversations.
Zhao et al. (2013)	Quasi-naturalistic study: about 108 participants drove an instrumented car along an urban highway in the U.S. The experiment did not include any mobile phone task. Instead, self-reported data was used.	Young adult drivers: 24.6 years (2.7) Middle aged drivers: 44.5 years (3.0) Older drivers: 63.3 years (3.1)	No differences were reported across age groups.

Appendix A. Details of the literature from 2010-April 2015

Figure A.1. (a) Distribution of articles according to their study design. (b) Distribution of articles according to the type of tool applied. (c) Distribution of articles according to data analysis techniques

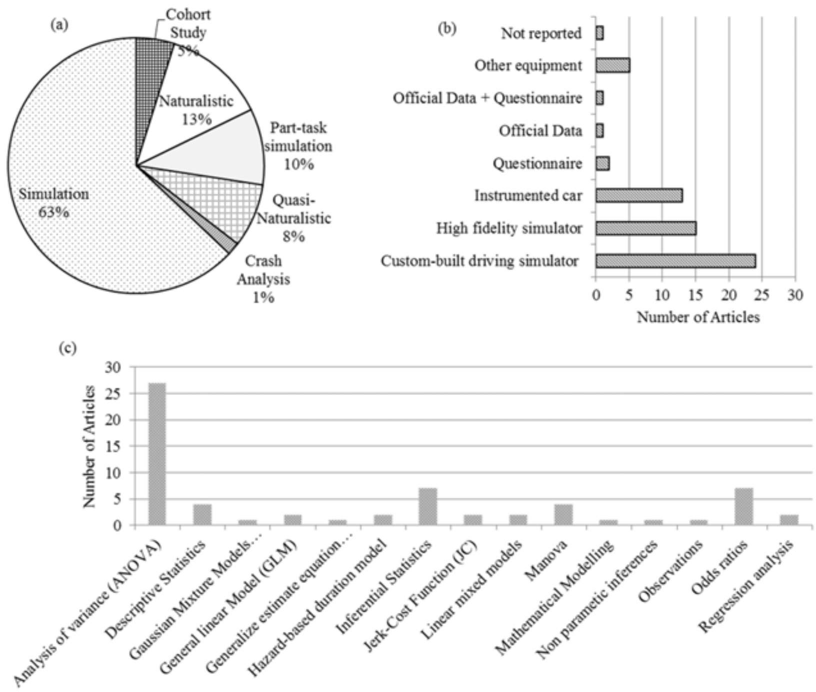


Figure A.2. (a) Distribution of articles according to mobile phone conversing interface. (b) Distribution of articles according to number of lanes included in the simulator study design. (c) Distribution of articles according road traffic environment included in the simulator study design.

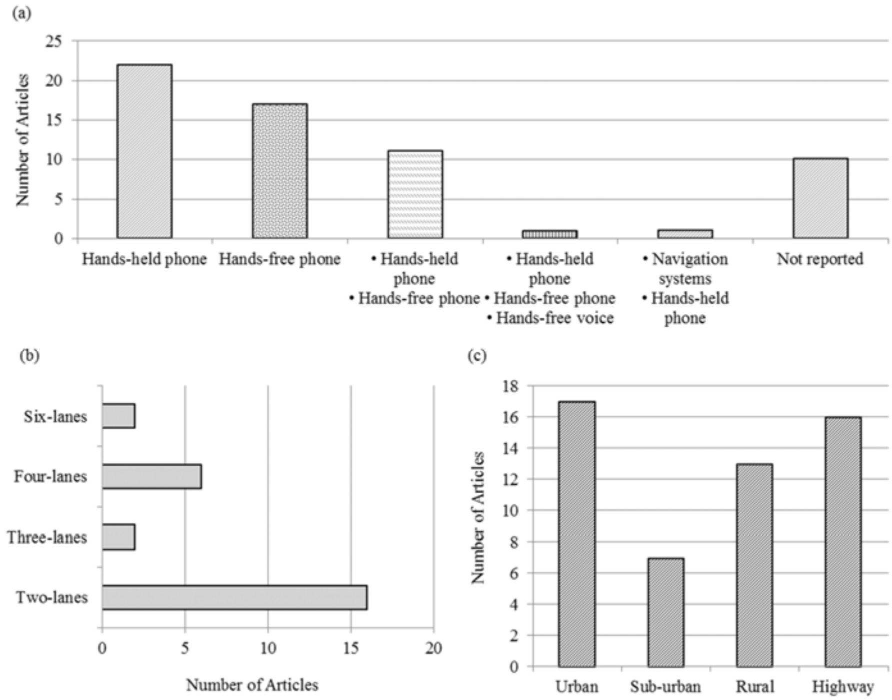


Figure A.3. Distribution of articles according to human-machine in-vehicle interactions