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Review of driving performance parameters critical for distracted driving research

Panagiotis Papantoniou*, Eleonora Papadimitriou, George Yannis

[a]*Department of Transportation Planning and Enginnering, NTUA, 5 Heroon Polytechniou str., GR-15773, Athens, Greece*

Abstract

While driving simulators allow for the examination of a range of driving performance measures in a controlled, relatively realistic and safe driving environment, driver distraction is a multidimensional phenomenon which means that no single driving performance measure can capture all effects of distraction. Furthermore, the large number of driving related outcomes each simulator provides, indicates that the decision regarding which measure or set of measures is used should be guided by specific criteria. The objective of this paper is a comprehensive review of driving performance parameters critical for distracted driving research. For this purpose an extended literature review took place in order to investigate the critical parameters which are examined in the scientific field of driver distraction. Firstly, all driving performance parameters examined in driving simulator experiments are identified and analysed including lateral control, longitudinal control, reaction time, gap acceptance, eye movement and workload measures, while a list of the most common driving simulator dependent variables is cited. Subsequently, a thorough literature review is carried out including 42 studies examining driver distraction through driving simulator experiments which were published in scientific journals, concern recent research and report quantitative results. In this framework, the respective driving performance measures are recorder aiming to investigate which and how they are analysed. A basic remark concerns the quantitative measures used to express driver distraction. In most cases, driver distraction is measured in terms of its impact to driver attention, driver behaviour and driver accident risk. It is noted that the specific measures used vary significantly. However, the diversity in the measures used, in combination with the diversity in the design of the experiments (i.e. road and traffic factors examined, number and duration of trials) often complicates the synthesis of the results, especially for the less commonly examined distraction factors.

Keywords: road safety; driver distraction; driving simulator; driving performance parameters

* Corresponding author. Tel.: +30 210 7721380; fax: +30 210 7721454.
E-mail address: ppapant@central.ntua.gr

1. Introduction

Road accidents constitute a major social problem in modern societies, accounting for more than 1.2 million fatalities in 2013 worldwide (WHO, 2014). Furthermore, human factors are the basic causes in 65-95% of road accidents (Sabey and Taylor, 1980; Salmon et al., 2011; Treat, 1980). The remaining factors include the road environment (road design, road signs, pavement, weather conditions etc.) and the vehicles (equipment and maintenance, damage etc.), as well as combinations of these three contributory factors.

Driver distraction constitutes a particular human factor of road accident causation. Driver distraction is generally defined as “a diversion of attention from driving, because the driver is temporarily focusing on an object, person, task or event not related to driving, which reduces the driver’s awareness, decision making ability and/or performance, leading to an increased risk of corrective actions, near-crashes, or crashes” (Regan et al., 2008). More specifically, driver distraction involves a secondary task, distracting driver attention from the primary driving task (Donmez et al., 2006; Sheridan, 2004) and may include four different types: physical distraction, visual distraction, auditory distraction and cognitive distraction.

The objective of this paper is a comprehensive review of driving performance parameters critical for distracted driving research. For this purpose an extended literature review took place in order to investigate the critical parameters which are examined in the scientific field of driver distraction. The paper is structured as follows. In the beginning, driving performance measures examined are presented and analysed including lateral control, longitudinal control, reaction time, gap acceptance, eye movement and workload measures. Then, an extended literature review is carried out regarding all available experiment types of assessing driver distraction. In the next step, a review of driving simulator studies on driver distraction is presented, based on specific selection criteria. More specifically, studies reviewed examine driver distraction through driving simulator experiments, were published in scientific journals, concern recent research and report quantitative results. Finally, the results are presented and discussed and some concluding remarks are provided.

2. Driving performance measures

As there are a lot of different methods and measures that exist for evaluating driving performance, the selection of the specific measures for driver distraction research, as in other areas of research, should be guided by a number of general rules related to the nature of the task examined as well as the specific research questions.

This chapter reviews a range of assessment measures that have been used in order to assess the impact of distraction on driving performance including lateral control, longitudinal control, reaction time, gap acceptance, eye movement and workload measures. Finally, a list of the most common driving simulator dependent variables is cited and some general remarks are provided.

2.1. Longitudinal control measures

A range of Longitudinal Control Measures can be examined in driver distraction research. Two of the most common are speed and headway which are further analysed below.

2.1.1 Speed

The relationship between speed and accidents is widely recognized in the road safety community and as such, speed is a commonly used dependent variable in transportation human factors research including driver distraction research. A number of speed related measures can be calculated including, average speed, speed variability, 85th percentile speed, maximum speed (Hogema and van der Horst, 1994; Manser and Hancock, 2007)

On distracted driving, the most common pattern is to adopt slower speed to increase available response time (Chu, 1994). Drivers use this strategy in order to exert some control over their circumstances and compensate for increased reaction time. It has also been shown that drivers display greater speed variability and throttle control while talking to the cell phone (Haigney et al., 2000; Rakauskas et al., 2004; Yannis et al., 2010; Beede and Kas, 2006).

2.1.2 Headway

Headway or vehicle following measures are also commonly employed in driver distraction research. Several measures have been commonly used including mean headway (distance or time based), minimum headway and standard deviation of headway. Headway is an indication of the safety margin that drivers are willing to accept, and thus, short headways are often interpreted as being indicative of degraded driving performance and a measure of high secondary task load (Regan et al., 2008).

A number of studies has shown, however, that drivers tend to adopt longer headways when interacting with secondary tasks, particular visual tasks (Greenberg et al., 2003; Östlund et al., 2004). For example, drivers engaging in a cognitively demanding cell phone conversation often maintain longer headway distance in a car-following situation as compared to when driving without a distraction task (Ranney et al., 2005; Strayer et al., 2003; Strayer and Drews, 2004). Furthermore, the distribution of headways for a given driver may reflect following preferences and the need to respond to surrounding traffic. Drivers who maintain a greater headway may have others pull into their headway gap. Certain drivers attempt to block others from pulling into a gap ahead, though at this point, there has never been a scenario designed to assess this behaviour (Dudek et al., 2006).

2.2. Lateral control measures

Lateral Control Measures assess how well drivers maintain vehicle position within a lane. These include lateral position, standard deviation of lateral position and steering wheel metrics. Lateral control measures can be sensitive to eyes off the road from distractions, perceptual-motor declines, and some cognitive declines. However, lateral control measures are also affected by the handling characteristics of the driving simulator, and the simulator vehicle may differ markedly from the one that the participant normally drives. More specifically, drivers may have more problems adapting to these differences in handling, and this may be especially problematic when frequent right and left turns are required. Consequently, it is vital that participants are given adequate practice so that they can get used to how the simulator vehicle handles (Regan et al., 2008).

2.2.1 Lateral position

Lateral position or Lane keeping refers to the position of the vehicle on the road in the relation to the center of the lane in which the vehicle is travelling. Decrements in lateral position control are used as a measure of secondary task load when evaluating the effect on in-vehicle distractions sources on driving performance (Greenberg et al., 2003; Green et al., 2004). An interesting finding with respect to lateral position is that moderate levels of cognitive load have been shown to lead to more precise lateral position, by reducing lane keeping variation (Engrom et al., 2005).

In two meta-analyses of the effect of cell phone usage on driver performance, Horrey & Wickens (2006) and Caird et al. (2008) found only a modest effect of distraction on lateral control, suggesting that cell phone conversation has minimal effect on lane keeping. A possible reason for these mixed findings is that the effects of distraction on lane keeping performance depend on the modality and demand of the secondary tasks. Visual, manual and cognitive distraction apparently have different effects on lane keeping performance (Liang & Lee, 2010)

2.2.2 Steering wheel control

Measures of steering wheel control have been used extensively in many forms of driving research. These include standard deviation of steering wheel angle, steering wheel reversal rate, steering wheel action rate, steering entropy. In driver distraction and workload research, steering wheel movements are considered to be an indicator of a secondary task load. When driving without any distraction source, drivers make a number of small corrective steering wheel movements to maintain lateral position while in distracted driving drivers often make a number of large and abrupt steering wheel movements to correct driving errors (Regan et al., 2008; Brooks et al., 2005; McGehee et al., 2004)).

In addition, cognitive distraction was found to increase steering wheel manipulation (Ranney et al., 2005; Seppelt and Wickens, 2003). In an on-road driving study, an auditory continuous memory task significantly increased the steering wheel reversal rate (with one degree gap threshold), compared to drive-only conditions (Engström et al., 2005).

2.3. Reaction time measures

Reaction time measures is an increasingly popular set of variables primary because of the relationship with accident risk. A range of reaction time measures can be examined including number of missed events, number of incorrect responses, reaction time and reaction distance. Drivers' ability to detect and react (most often at unexpected incidents) has been shown to be impaired by in vehicle distraction sources, particularly with complex devices. In this framework, a number of studies has shown that handheld or hands free phone increases driver's reaction time by up to 30% (Yannis et al., 2010; Horrey and Wickens, 2006; Ishigami and Klein, 2009; Hancock et al., 2003).

Furthermore, several studies have examined the influence of driver demo-graphics like age and gender on reaction times of distracted conditions. Similar impairment of reaction times was reported by Caird et al. (2008), where there action times were 0.46 s and 0.19 s slower, respectively, for distracted older and young drivers. An experiment on an advanced driving simulator by Nilsson and Alm (1991) showed that elderly drivers' reaction times to an unexpected event were approximately 0.40 s greater than that for young drivers when distracted by a cell phone conversation.

2.4. Gap acceptance measures

Despite its importance, not many studies have been conducted on modeling passing gap acceptance behaviour. Early studies in this area discussed drivers' perception of the required gaps for passing (Jones and Heimstra, 1966; Farber and Silver, 1967; Gordon and Mast, 1968) while other studies focused on examining the major components of the passing process and factors which affect this process, such as the required sight distances (Polus et al., 2000; Glenon, 1998; Brown and Hammer, 2000; AASHTO, 2004).

Negotiating gaps in traffic is a complex task requiring considerable visual guidance and attention. Gap acceptance measures that have been used in distraction research include number of collisions initiated and gaps accepted. Research shows that when using in vehicle distraction sources such as cell phones, drivers tend to accept shorter gaps in traffic when turning compared to undistracted driving (Farah et al., 2007).

2.5. Eye movement measures

It has become increasingly common to use eye movement systems in driving simulator studies although there is a number of limitations that have to be carefully considered. Furthermore, fixations, saccades, and smooth pursuits represent three types of eye movements that can be used to help identify cognitive distraction. Fixations occur when an observer's eyes are nearly stationary. The fixation position and duration may relate to attention orientation and the amount of information perceived from the fixated location, respectively (Hayhoe, 2004). Saccades are very fast movements that occur when the eyes move from one point of fixation to another. Smooth pursuits occur when the observer tracks a moving object, such as a passing vehicle. They serve to stabilize an object on the retina so that visual information can be perceived while the object is moving relative to the observer. In the context of driving, smooth pursuits have a particularly important function; they capture information from the dynamic driving scene. Both fixations and smooth pursuit movements may reflect the how cognitive distraction interferes with how drivers acquire visual information (Liang et al., 2007).

2.6. Workload measures

There is still no universally accepted definition for mental workload. One proposed definition is: "Mental workload is a hypothetical construct that describes the extent to which the cognitive resources required to perform a task have been actively engaged by the operator" (Gopher, 1986). Another definition of mental workload proposed by Verwey (2000) is that "mental workload is related to the amount of attention required for making decisions." Just defining the concept of workload is not enough; there must also be a way to measure it. Since there is not even an accepted definition of workload, it is not surprising that there is not a single way to measure it either. There are three main classifications for measurement of workload: physiological, subjective, and performance-based measures (Miller, 2001).

2.6.1 Subjective measurement

Subjective measurement of levels of workload is based on the use of rankings or scales to measure the amount of workload a person is feeling. Subjective workload measures are devoted primarily to the intermittent question-answer type response to varying levels of workload. The two main types of scales used to measure subjective workload are unidimensional and multidimensional scales (Miller, 2001).

Unidimensional rating scales are considered the simplest to use because there are no complicated analysis techniques. The unidimensional scale has only one dimension. Generally, the unidimensional scale is more sensitive than the multidimensional scale (De Waard, 1996). The multidimensional workload scale is considered to be a more complex and more time consuming form of measurement, and has from three to six dimensions. The multidimensional scale is generally more diagnostic (De Waard, 1996).

Several simple subjective mental workload scales have been developed to measure an individuals' perceived workload. Some of the main scales used in the driving domain include NASA-task Load Index (TLX), Rating Scale Mental Effort (RSME), Situation Awareness Global Assessment Technique, Driving Activity Load Index (DALI) (Miller, 2001).

2.6.2 Physiological measurement

Physiological measurement of workload is a factually based concept that relies on evidence that increased mental demands lead to increased physical response from the body (Moray, 1979). Physiological workload measures are devoted primarily to continuous measurement of the physical responses of the body.

Most research focuses on five physiological areas to measure workload: cardiac activity, respiratory activity, eye activity, speech measures, and brain activity. Cardiac activity is measured through heart rate, heart rate variability, and blood pressure. Respiratory activity measures the amount of air a person is breathing in and the number of breaths in a given amount of time. Eye measures mainly include horizontal eye movements, eye blink rate, and interval of closure, but there are several other less accepted measures. Speech measures take pitch, rate, loudness, jitter, and shimmer into account when determining workload. To measure brain activity, either the electroencephalograph (EEG) or electro-oculogram (EOG) are usually used (Miller, 2001).

2.6.3 Performance measurement

"Performance may be roughly defined as the effectiveness in accomplishing a particular task" (Paas & Vanmerrienboer, 1993). The two main ways to measure workload by means of performance are primary and secondary measures. The basis for using primary and secondary tasks to measure workload is based on the assumption that people have limited resources (Yeh & Wickens, 1988). Derrick (1988) explains how the "tasks that demand the same resource structure will reveal performance decrements when time-shared and further decrements when the difficulty of one or both is manipulated." This means that workload can be estimated by measuring the decrease in performance by either the primary or secondary tasks. The primary task measure is a more direct way to measure workload than the secondary task measure, but both are used and at least moderately accepted.

3. Driver distraction experiments

In this section, an extended literature review is carried out regarding all available experiment types of assessing driver distraction. More specifically, benefits and limitations are presented regarding Naturalistic Driving

Experiments, Driving Simulator Experiments, On-road experiments, In Depth Accident Investigations and Surveys on Opinion and Stated Behaviour.

3.1. On-road experiments

In On-road experiments studies, an instrumented vehicle is equipped with instrumentation to take recordings of a variety of aspects of driving (Rizzo et al., 2002). These technologies include GPS, video-cameras, sensors, accelerometers, computers, and radar and video lane tracking systems. On-road experiments attempt to gain greater insights into the factors that contribute to road user accident risk and the associated accidents factors at specific conditions. These investigations are conducted by trained experts from multiple disciplines to collect as much useful information as possible, to be of maximum benefit in answering current research questions and any that may arise in the future (Papantoniou et.al, 2015).

3.2. Naturalistic Driving

Naturalistic Driving is a relatively new research method for the observation of everyday driving behaviour of road users. For this purpose, systems are installed in participants' own vehicles that register vehicle manoeuvres, driver behaviour (such as eye, head and hand manoeuvres) and external conditions. In a Naturalistic Driving study, the participants drive the way they would normally do, in their own car and without specific instructions or interventions. This provides very interesting information about the relationship between driver, road, vehicle, weather and traffic conditions, not only under normal driving conditions, but also in the case of incidents or accidents (SWOW, 2010).

3.3. Driving simulators

Driving simulators allow for the examination of a range of driving performance measures in a controlled, relatively realistic and safe driving environment. Driving simulators, however, vary substantially in their characteristics, and this can affect their realism and the validity of the results obtained. Fidelity refers to the level of realism inherent in the virtual world. The closer a simulator approximates real-world driving, in terms of the design and layout of the controls, the realism of the visual scene, and its physical response characteristics, the greater fidelity it is reported to have (Godley, Triggs and Fildes, 2002; Triggs, 1996). Simulator validity typically refers to the degree to which behaviour in a simulator corresponds to behaviour in real-world environments under the same condition (Kaptei et al., 1996).

3.4. In-depth accident investigations

In-depth accident investigations are conducted by trained experts from multiple disciplines to collect as much useful information as possible in order to describe the causes of accidents and injuries. The aim of these studies is to reveal detailed and factual information from an independent perspective on what happened in an accident by describing the accident process and determine appropriate countermeasures (Papantoniou et.al, 2015).

3.5. Surveys on Opinion and Stated Behaviour

In stated behaviour surveys, a reference questionnaire is built, based on a list of selected topics and a representative sample of population is interviewed. The survey approach can employ a range of methods to answer the research questions such as postal questionnaires, face-to-face interviews, and telephone interviews (Papantoniou et al., 2015).

Table 1. Review of driving performance measures

			Distraction Source							Sample Characteristics							Driving performance measures								Statistical Analyses			
	Authors	year	cell phone	conversation	visual	music	IVIS	advertisign signs	eat, drink, alcohol	sample size	% male	25-	26-55	55+	benefits	questionnaire	speed	lane position	reaction time	perception / situation awareness	headway	accident probability	eye glance	acceleration / deceleration	Descriptive statistics	One way ANOVA	Two way ANOVA	Repeated measures ANOVA
1	Laberge et.al	2004	●	●						80	50%	●				●	●	●								●		
2	Drews et.al	2008	●	●						96	25%	●	●		●		●	●								●		
3	Charlton	2009	●	●						112	50%	●	●	●	●	●	●				●	●					●	
4	Yannis et.al	2011	●	●					●	42	48%	●			●	●	●	●	●			●						●
5	Hunton andRose	2005	●	●						111	25%				●							●				●		
6	Horbery et al	2006	●			●				31	-		●	●		●	●										●	
7	Reed-Jones et	2008	●			●				32	44%	●					●					●				●		
8	Yannis et.al	2011	●			●				48	50%	●				●	●	●	●			●				●		
9	Rakauskas et al	2004	●							24	50%					●	●	●				●					●	
10	Kass et al	2007	●							49	49%	●	●	●												●		
11	Bruyas et al	2009	●							30	50%	●	●		●	●												●
12	Reimer et al	2010	●							60	60%	●			●	●	●			●				●		●		
13	Schlehofer et al	2010	●							69	36%	●			●	●											●	
14	Ma and Kaber	2005	●				●			18	50%	●				●	●	●			●					●		
15	Beeder and Kas	2006	●				●			36	-	●	●			●	●	●	●								●	
16	McKnight and Mc	1993	●				●			150	50%	●	●	●						●						●		●
17	White et al	2010		●						40	50%	●				●						●				●		●
18	Maciej et al	2011		●						33	52%	●			●	●												
19	Noy et al	2004			●					24	63%	●	●		●	●	●									●		●
20	Donmez et al	2006			●					28	-		●	●	●	●										●		
21	Donmez et al	2008			●					48	52%	●			●	●	●	●			●	●	●			●		●
22	Liang et al	2010			●					16	50%	●	●		●			●		●						●		●
23	Fofanova et al	2011			●					20	80%			●			●									●	●	
24	Muhrer et al	2011			●					28	50%	●	●		●	●	●				●						●	
25	Metz et al	2011			●					40	55%		●										●					
26	Kaber et al	2012			●					20	50%	●			●	●										●		
27	Zhang et al	2012			●					24	50%	●	●	●		●	●						●					●
28	Hatfield et al	2008				●	●			27	48%		●		●	●	●	●		●		●						●
29	Chisholm et al	2008				●				19	53%	●			●			●		●			●			●		
30	Garay-Vega et al	2010				●				17	71%	●	●		●	●							●					●
31	Young et al	2012				●				37	46%	●	●		●	●	●	●								●		
32	Hughes et al	2012				●				21	5%	●	●			●	●	●										●
33	Jamson et al	2005					●			48	-		●															●
34	Donmez et al	2007					●			29	48%	●			●	●	●							●		●		
35	Reyes et al	2008					●			12	50%		●		●				●					●		●		●
36	Jamson et al	2010					●			18	50%		●		●		●	●								●		●
37	Benedetto et al	2011					●			15	80%					●			●							●		●
38	Birrell et al	2011					●			25	56%		●			●	●				●			●		●		●
39	Terry et al	2008						●		78	55%	●	●	●		●			●		●						●	
40	Young et al	2009						●		48	60%		●		●			●					●			●		
41	Bendak et al	2010						●		12	100%	●	●			●	●						●		●			
42	Edquist et al	2011						●		48	63%	●	●	●	●	●		●					●			●		
43	Rakauskas et al	2008							●	45	100%	●			●											●		
44	Young et al	2008							●	26	62%	●	●	●	●		●	●									●	
45	Harrison et al	2011							●	40	50%	●	●		●	●	●					●				●		

4. Review of driving performance measures in driving simulator research

In Table 1 a review of 45 driving simulator studies on driver distraction is presented, based on specific selection criteria. More specifically, studies reviewed examine driver distraction through driving simulator experiments, were published in scientific journals, concern recent research and report quantitative results.

To begin with, the distraction sources examined and the sample characteristics are summarized in the first part of Table 1. In almost all studies examined, distraction was induced in some way by the experimenter, often by letting the participant perform a secondary task. These tasks can correspond more or less to what drivers might do in real traffic. The tasks may be visual, auditory, motor or combined, they may be simple or complicated, and they may require immediate attention or leave the driver some leeway in deciding when to attend to the task. A large number of simulator studies concern cell phone distraction while driving, and its comparison with other distractions. Conversation with passengers and manipulation of in-vehicle information systems are often examined. For the other distraction sources, only a small number of simulator studies were available.

The basic remark concerns the quantitative measures used to express driver distraction. In most cases, driver distraction is measured in terms of its impact to driver attention, driver behaviour and driver accident risk. It is noted that the specific measures used vary significantly, and the driving performance measures can be ranked as follows, in terms of frequency: speed, lane position (position of vehicles, crossing the center of median lane, steering angle), accident probability, number of eye glances, headway, reaction time, overtaking, acceleration and deceleration, and hazard/risk perception and situation awareness (based on probing participants). Certainly, the effects of distraction need to be studied on a variety of different driving performance measures to better understand which measures of driving might be most vulnerable to the disruptive effects of distraction.

However, the diversity in the measures used, in combination with the diversity in the design of the experiments (i.e. road and traffic factors examined, number and duration of trials) often complicates the synthesis of the results, especially for the less commonly examined distractors. For example, reaction times at unexpected incidents have been found to be very sensitive to several distraction sources and can be directly interpreted in terms of safety; however, there is little or no information on the effects on reaction times for some key distractors such as the IVIS. On the other hand, mean speed and acceleration are examined by the majority of researchers in terms of distracted driving and the related effects are very well documented, therefore it may be suggested to shift the research focus on other measures. As another example, time or space headways may be less appropriate measures as they heavily depend on the type of simulated ambient traffic (i.e. whether the lead vehicle behaviour is explicitly simulated or is left random).

Another related remark can be made: studies focusing on visual distraction are – naturally – more focused on driver attention measures (e.g. eye glances etc.), while studies examining motor and cognitive distractors such as cell phones are more directly concerned about driving performance measures (e.g. Speeding, lateral control etc.). This diversity, despite its advantages, limits the potential for using the existing studies in order to answer more global questions related to driver distraction.

5. Conclusions

The objective of this paper is a comprehensive review of driving performance parameters critical for distracted driving research. For this purpose three different reviews took place regarding driving performance measures, driver distraction experiments as well as driving performance measures in driving simulator research. Several conclusions are extracted from each individual review as presented below.

Driver distraction is a multidimensional phenomenon which means that no single driving performance measure can capture all effects of distraction. The large number of measures indicates that the decision regarding which measure or set of measures is used should be guided by the specific research question (Regan et al., 2008). However, recent research offers valuable insights into what measures are most appropriate for particular evaluations. More specifically, visual distraction has a greater effect on lateral control measures, whereas cognitive distraction affects more visual scanning behaviour. Furthermore, the type of distraction source being assessed should influence measurement selection.

All types of experiments should carefully follow some basic experimental design principles, allowing for reliable analysis of the data in order to provide appropriate answers to the research questions examined. Moreover, there are various other analysis challenges that need to be addressed when assessing distracted driving, such as the selection of appropriate and relevant driving performance measures, the application of appropriate analysis techniques, and the reliability and validity of the analysis. Consequently, the selection of method for the assessment of distracted driving performance should be carried out in accordance to the specific objectives or research questions of the assessment, the time-frame and the infrastructure or resources available etc.

Regarding driving performance measures the respective review presented in this research revealed that a lot of different methods and measures exist for evaluating driving performance the most common of which include lateral control, longitudinal control, reaction time, gap acceptance, eye movement and workload measures. In most cases, driver distraction is measured in terms of its impact to driver attention, driver behaviour and driver accident risk. It is noted that the specific measures used vary significantly. However, the diversity in the measures used, in combination with the diversity in the design of the experiments (i.e. road and traffic factors examined, number and duration of trials) often complicates the synthesis of the results, especially for the less commonly examined distraction factors.

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