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A meta-analysis of the impacts of operating in-vehicle information systems on road safety

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ABSTRACT

This study aims to estimate the overall impact of distraction due to operating in-vehicle information systems (IVIS) and similar devices while driving on road crashes. While similar research has been undertaken investigating the issue, varying results have been reported so far. Therefore a two-step approach was adopted: initially a review of the literature was conducted to identify key high quality studies and the parameters that they examined. Afterwards, meta-analyses were applied in order to estimate the overall effects of operating IVIS while driving on the absolute proportion of crashes (i.e. the proportion of total crashes due to IVIS). After applying a random effects meta-analysis to the findings of existing studies, it was found that 1.66% of crashes occur due to operating devices in total. In addition, it is indicated that about 0.6% of safety-critical incidents for professional drivers are due to in-vehicle device operation. The odds of crashes influenced by IVIS operation were also estimated and were found to be very low. From the findings of the present review and the meta-analysis, it is suggested that device operation as a risk factor while driving is a less researched aspect of driver distraction than others, and more studies would improve result estimates and transferability, especially for professional drivers. This study summarizes concisely the current effect of driver interaction with in-vehicle information systems on crashes, which might become considerably pertinent in view of the increasing deployment of vehicles with increasing levels of automation.

1. Background and objectives

As modern vehicles have become more complex and sophisticated, various informatics devices that do not fall under a narrow category have been created and are being operated by drivers regularly. Those can be built-in auxiliary devices, such as air-conditioning or a car lighter, or various information system devices. The term in-vehicle information system (IVIS) encompasses most of the last category, which can be assistant devices such as GPS systems, traffic information systems, eco-driving systems, email interfaces, vehicle diagnostics, and, in some situations, warning systems and emergency assistance systems. A large number of professionals in the transport sector have come to adopt the use of such devices, also within the framework of fleet management systems, and the variety of their uses is similar, for example location and position information, vehicle handling information, military applications etc.

In the context of road safety, engagement with those devices induces a level of distraction to the driver. Driver distraction is well known as a major risk factor in road safety, which comprises several sub-categories and is closely related to driver inattention, though the two terms are not identical [1]. The additional amount of mental workload and motor dual-tasking that drivers have to undertake influences their behavior, reduces their reflexes and slows reaction times to events (both the time to mentally register the effect and the time to physically react to it) [2–4]. In the case of devices with screens present, drivers spend some time with their eyes fixed on the screen instead of the road, which can also lead to crashes, near misses, and other critical safety events (such as those modeled in [5]). The famous 100-car naturalistic study in the US determined that visual distraction, which screen devices induce, is a key element in crash and near-crash involvement [6].

The examination of the impacts of IVIS and similar device operation has received less attention in the literature, compared to mobile phones and other distractors [7]. There have been a number of studies examining the distraction caused by operating devices, similarly there has been a variety of methods and results there-in. A recent review on correlating in-vehicle information systems and fuel efficiency highlights the need for more interdisciplinary research to reach definitive and well

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substantiated results [8]. Individual studies argued that some devices, like navigation systems, do not cause situations that are detrimental to road safety [9], while others have identified significant negative effects [10], and an overall assessment and synthesis of findings is necessary.

The topic warrants further consideration not only for the safety of the drivers, but for the safe development of related technology applications, as these devices should not facilitate driving activities such as navigation at the expense of safety. This is especially true for many professional drivers (such as those examined in [11]) who drive vehicles of significant mass, which can be especially dangerous to many road users, or operate them in unusual circumstances, for instance in construction sites. Moreover, in view of rapidly increasing penetration of more and more in-vehicle information systems in the coming years, towards an era of semi-automated vehicles and dual control situations, the safe interaction of drivers with vehicle systems and related interfaces needs to be ensured [12,13], and in this framework the synthesis of existing knowledge will be useful.

In this framework, the objective of the present research is to use meta-analysis techniques to estimate an overall credible estimate of the impact of operating in-vehicle information systems on road safety. More specifically, the proportion of total crashes due to operating in-vehicle devices will be estimated.

The remainder of the paper comprises the following: firstly, an overview of existing literature is provided and afterwards the data section provides an overview and a short description of studies considered in the meta-analyses as well as the selection criteria. The methodology section illustrates the theoretical background for fixed and random effects meta-analyses. Tests for detecting and correcting publication bias are also presented. The results section presents the meta-analyses and modelling results of the study. Finally, the conclusions section presents the main conclusions drawn and implications from the study results, together with suggestions for further research on the topic.

2. Literature overview of the impact of in-vehicle device operation impact on road safety

For the assessment of the available scientific knowledge, a literature overview was conducted. The databases searched were Scopus, Google Scholar and TRID. The search terms used for the topic were "in-vehicle information systems" OR "operating devices" AND "distraction" OR "interaction". Findings are separated by examined road safety parameters.

Several studies traditionally investigate direct indicators of road safety such as crash frequency and/or severity, as well as relevant events such as near crashes (or near misses), which are treated as road safety critical situations.

2.1. Impact on crashes

In one of the earlier attempts on monitoring driver distraction, Wang et al. [14] who exploited data from the 1995 US Crashworthiness Data System in order to evaluate more in-depth information on driver inattention related crash causes. Several percentages of crashes involving inattention or distraction were provided; adjusting climate controls and adjusting other devices or in-vehicle objects were each found responsible for 0.2% of total crashes.

Another study in the early 2000s anticipated that the development of IVIS would lead to driver overload [15]. Descriptive statistics data from Japan were used for crashes related to navigation systems. It was found that they were considered responsible for 1.1% of the total fatalities, though the fatality sample was arguably limited. The author further reports that approximately one third of navigation-related crashes are associated with device operation.

In a study focused on England and Wales, Stevens and Minton [16] utilized police fatal accident reports to determine the impacts of several categories of in-vehicle distraction. Specifically, information devices were considered in two forms, new (including electronic route guidance and congestion warning displays, computers, etc.) and old (vehicle instruments etc.), among other categories. While information devices were a very low-ranking distraction category, it is recognized that study data originate before the widespread use of information systems (before 1993) and that their ranking of the database might change in the future.

A research report by Stutts et al. [17] examined various distraction categories, which included categories for adjusting vehicle/climate controls. The report was based on data from a five year period (1995–1999), obtained from the US Crashworthiness Data System. It was concluded that these activities were not as frequent as some of the other sources of distraction, with them being apparent in only 2.8% of the distracted driver population (the category "other devices/objects" which could have also been pertinent to IVIS was examined separately and appears in 2.9% of the crash-involved driver population respectively). From all examined drivers involved in crashes, distracted drivers accounted for 8.3% of the total. It was mentioned, however, that exposure differences of said distraction categories was not represented in the dataset.

McEvoy et al. [18] interviewed drivers that were hospitalized after a crash in Perth, Australia. They used questionnaires and supplemented their data from medical records. It was found, among other results, that 31.7% of drivers cited distraction as present at the time of the crash, with adjusting in-vehicle equipment being responsible for 2.5% of all crashes; adjusting in-vehicle equipment comprised adjusting the stereo, air conditioning, windows and 'other' factors. Furthermore, the authors recognized the lack of a standardized distraction taxonomy up to the date of the study.

Neyens and Boyle [19] assessed the impact of several distraction factors on crashes of teenage drivers. For crashes involving a form of distraction for the driver, distraction related to interaction from in-vehicle sources was ranked second, after cognitive distractions. However, this was a broader category comprising consumption of goods (eating, drinking), moving objects inside the vehicle etc. along with operating in-vehicle information systems. The authors note that drivers distracted by in-vehicle items or devices, were more likely to be involved in rear-end or fixed-object collisions compared to angular collisions.

In a subsequent study, Neyens and Boyle [20] explored the effects of operating devices on crash injury severity. They reported that teenage drivers are more likely to be involved in a severe injury crash if distracted by a cellphone or passengers rather than in-vehicle devices. Interestingly enough though, the passengers of distracted teenage drivers were also more likely to be severely injured when the driver was distracted by a cell phone, in-vehicle device or even the passengers themselves. This highlights a possible secondary risk from IVIS interaction which might be counterintuitive initially.

2.2. Impact on critical events from naturalistic studies and questionnaires

A research report presenting the findings of the 100-car naturalistic driving study by Klauer et al. [6] analyzed driver distraction and their impact on crashes and near-crashes. Findings include, among others, that visual or manual tasks that have increased complexity – which included operating and viewing a PDA (personal digital/data assistant) – result in up to three times higher crash and near crash risk (odds ratio methods) compared to baseline driving. Short glances of drivers away from the roadway (≤2.0 s) were found to be safer than longer glances. Relevant analytical results and data are given in another research report as well [21].

With a more specific target group, Hanowski et al. [22] investigated driver distraction in long-haul truck drivers. This study used data from the 100-car naturalistic driving study. 41 long-haul truck drivers were examined for various distraction activities, and 2737 safety critical events were recorded, though no actual crashes happened. Apart from safety critical events, driver glance characteristics were examined as well. It was concluded that critical crashes occurred under a combination of increased task complexity and visual demand, among other findings. Certain distraction factors relating to information devices were recorded such as professional driver radio use and looking at an instrument panel.

A research report by Olson et al. [23] combined data from two naturalistic driving studies comprising 55 trucks at 16 locations. The aim was to explore the impact of driver distraction in commercial vehicle drivers. Several safety-critical events were examined along with regular crashes. It was determined that drivers were engaged in non-driving related tasks in 71% of crashes, and that increased task complexity leads to significant risk increases. Specifically, interacting with or looking at a dispatching device led to an odds ratio for a safety-critical event of 9.93 for professional drivers, using or reaching another electronic device (e.g. radio) led to an odds ratio of 6.72 and adjusting an instrument panel led to an odds ratio of 1.25. All these were reported as statistically significant values. Furthermore reaching for an in-vehicle object and interacting with or looking at a dispatching device were also calculated to have the highest and second highest population attributable risk percentages, respectively.

Lansdown [24] conducted an anonymous online questionnaire self-reporting survey in order to collect data regarding the impact of driver distraction on crashes, as well as near misses. The most distracting driver behaviors were reported to be writing/reading text messages and conversing via a hand-held cellphone device. What is also interesting to the scope of the current research is that apart from interaction with children, the most frequent distraction factors were reported to be both route guidance destination entry with 2% (near misses = 2.8%) and use of an add-on media device 'e.g., an iPod' with 2% (near misses = 3.9%), and three items reading a text message. It is noteworthy that text messages do not necessarily relate to cellphones, and might thus apply to IVIS or other devices as well.

Another notable study is that of Klauer et al. [25] who conducted a naturalistic driving study by monitoring the vehicles of new and experienced drivers with several instruments. Several crash and near-crash events were observed during the study. Device related tasks were separated into two categories; one included radio, HVAC (heating, ventilation and air-conditioning) or other internal vehicle system with controls on the dashboard and the other included other controls (such as sun visor). The analysis showed that both categories had a crash and near-crash odds ratio higher than one for novice drivers, but lower than one for experienced drivers. Additionally, the first category which included dashboard-related IVIS had lower odds ratios in both cases, which might hint at a more preferable IVIS design as regards road safety, which is further supported by their conclusion that "the secondary tasks associated with the risk of a crash or near-crash all required the driver to look away from the road ahead."

Victor et al. [26] presented the findings of the SHRP2 naturalistic driving study. Videos were coded and reviewed depending if they were present in a small time-window preceding the crash. Several distracting activities were considered and aggregated; ultimately the aggregate portable electronics visual-manual distraction group was found to be the one with most substantial risk (odds ratio = 2.7). This distraction group included locating/reaching for/viewing/operating a PDA, along with screen-related variables for cellphones such as texting and dialing. Another noteworthy finding was that other well-known distractions, such as answering a cellphone or distractions external to the vehicle, were not found to be significantly risky.

Dingus et al. [10] performed in-depth analyses of crashes via video observations and measurements of 3542 drivers recruited for a large naturalistic driving study program in the US. They utilized a case-cohort approach for each of the considered contributing factors. The naturalistic driving dataset comprised 905 crashes, which allowed a direct analysis of causal factors using only crashes. It was found that reaching for an object that was not a cellphone had considerable risk (odds ratio of crash to baseline: 9.1). Regarding device operation, it was found that the overall in-vehicle device related odds ratio was 2.5, which rose to 4.6 when climate adjustment devices were not considered. While interpreting the results, it is mentioned in the study that distracting activities that engage the drivers' eyes away from the forward roadway present the highest risk.

2.3. In-vehicle information device operation impact on indirect safety indicators

There are other groups of studies that explore other road safety variables, such as driving regulation violations or speed-related variables. Furthermore, behavioral variables such as glance patterns (or proportions of total eyes-off-road time) are long proven to be associated with crash risk. This is especially true as glance duration increases [27], especially longer than two seconds [28,29]. Furthermore, Victor et al. [26] determined that eyes-off-path glance behavior was a potent risk indicator, while ultimately used a linear combination of three glance metrics to accurately predict crashes and near-crashes.

Horberry et al. [30] conducted a simulator study in which they categorized drivers into three age groups and distracted them with two different tasks: an easier auditory/vocal task involving cellphone use and a more demanding visual/manual task involving the adjustment of an in-vehicle entertainment system. Mixed factorial ANOVAs showed that performing an additional in-vehicle task is detrimental in some situations regarding driving performance. While it is understood that listening to music constitutes another type of distraction, physical interaction with the entertainment system was found to negatively influence the maintaining of speed and preparedness to react to unexpected hazards of drivers, for simple and complex environments and across all age groups.

Reyes and Lee [4] focused on the exploration of the additional cognitive load imposed by IVIS throughout three conditions, namely IVIS interaction, pause between IVIS interactions and baseline without IVIS. Participants drove in a simulator which allowed for the examination of several variables: brake and accelerator release times, bicycle detection and eye-fixation performance. It was important that, contrary to the authors' initial hypothesis, driver braking parameters were uniform across all conditions. However, reaction times were longer for bicycle detection, hinting at diminished sensitivity to peripheral vision events. Some negative effects were reported as persisting even after the IVIS interaction had stopped, while eye movements were influenced by IVIS conditions but not by task duration.

Fu et al. [31] examined a wider range of factors and their influence on driving violations at intersections. In-vehicle related distractions, which were a different category from passenger interactions, were found to increase speeding related violations and traffic sign and signals violations by 4.76 when compared to turning-yielding-signaling violations.

Xie et al. [32] performed a dual experiment to measure the impact of IVIS including both an on-road testing and a simulator experiment. They used instrumentation to monitor eye-tracking behavior for drivers. From several IVIS positioning configurations specific patterns were determined (e.g. right horizontal regions). Drivers also reported there were more and less favorable IVIS positioning configurations. Subjective rating for tasks was also reported, and manual responding was found to be more taxing (namely demanding in attention) than oral responding.

Peng et al. [33] conducted a simulation study researching the impact of IVIS text on driving behavior, arguing that IVIS texts are designed to be relevant to the task of driving as opposed to cellphone texting. Results showed that irrelevant text present in IVIS did not degrade vehicular control performance significantly for drivers, but it did increase the time required to complete the reading task itself. Furthermore, longer phrases did not cause more errors than shorter ones. It is mentioned, however, that all IVIS text reading tasks significantly increased standard deviation of lane position and mean and standard deviation of time headway.

Another naturalistic driving study was conducted by Metz et al. [9] who monitored 99 drivers for three months who were using two different interface configurations of navigation systems (portable and integrated). It was observed that drivers preferred to handle the navigation systems in low or zero speeds, and they compensated for their use with decreasing speed and increasing following distances (headways). The authors also report that there was no increase in road-safety critical events (crashes and near-crashes), but admit that the overall traffic safety impacts are hard to determine, mainly because the relation of near-crashes to crashes is not completely understood yet.

Morris et al. [34] carried out a dual study investigating the glance behavior of drivers while they were using (i) a navigation device and (ii) an ecological ('green') driving advisory device. The subjects, who were novice users of navigation devices, were required to drive prescribed routes. Video data was analyzed from both test sites. For the first study, which involved using a navigation device resulted in an increase of eyes-off-road time and average glance duration (though not dramatically). Moreover, glances to a navigation device were found to be responsible for the majority of the increase in eyes-off-road time. Regarding the second study, it was found that the number of glances were similar for the green driving support system and the baseline. The authors conclude that any increase in eyes off-road-time should be treated cautiously, and future smart in-vehicle information systems designs should consider auditory interface only 'when complex road situations arise'.

Purucker et al. [35] also investigated total eyes-off-road time as a result from IVIS exposure (alongside cellphones and music devices) by conducting two subsequent simulator studies. They utilized keystroke level modelling and participant age to initially predict and determine total eyes-off-road time duration in the first study and afterwards validate these predictions in the second. Complex manual entry in a navigation device (full-street address entry) was found to be the most distracting activity. The authors claim that their findings can be used for total eyes-off-road time prediction when designing and developing device configurations.

An earlier study concerning methods of assessment of the influence of IVIS on driver behaviour is also worth mentioning [36]. The authors conducted a series of 9 experiments on a simulator and performed analyses on trajectory, speed fluctuation, response time, heart activity and other measures, and provided a wealth of measurements, though without advanced statistical modelling. They concluded that even expert and participant evaluations are not objective because of the subjective nature of the persons involved. Participants might classify certain devices as dangerous, while their measured impact on road safety is not significant. In light of these findings, the current analytic approach hopes to circumvent much of the uncertainty in personal factors via a random-effects meta-analysis, as will be explained in the following.

Considering the examined parameters for IVIS, a relevant important study is that of Harvey et al. [37] which developed a framework for evaluating IVIS with the aim of focusing on usability without compromising safety of drivers. The authors assessed over 70 usability evaluation methods for IVIS and selected 13 for inclusion in the framework. From an engineering/road safety point of view, which is the scope of the present study, sustained effectiveness, sustained efficiency and interference were considered as the three safety criteria for IVIS. Most of the indicators present in previous studies were found to be matched with said criteria (lateral/longitudinal control, event detection and visual behaviour, driver load, task errors etc.). Further approach of the paper was more conceptual rather than statistical, however.

Considering the analysis approach of the impact of IVIS operation on indirect safety indicators, the examined studies utilized one or more of several available methodologies. Most studies provided initial descriptive statistics of their gathered data. Some conducted forms of analysis of variance (ANOVA) (Reyes and Lee [4], Victor et al. [26], Horberry et al. [30], Xie et al. [32], Metz et al. [9]) or *t*-test and F-test approaches (Reyes and Lee [4]), Morris et al. [33]). Other studies, deployed more advanced forms of modelling: logistic regression, (Victor et al. [26], Fu et al. [31]), factor analysis (Reyes and Lee [4]), linear mixed models (Peng et al. [33]) or multiple log-linear analysis and keystroke level modelling (Purucker et al. [35]).

2.4. Summary of methods

The international literature has examined a variety of methods to study the effect of operating devices on road safety. Sometimes this risk factor is examined alongside other similar distraction factors such as interaction with passengers and cell phone use, for instance in a study by Lansdown [24], and sometimes it is studied on its own, for instance in a study by Reyes and Lee [4]. Consequently, the relevant examinations or analyses may or may not be adjusted to capture this particular type of distraction or the entire situation in any given case.

Given that it is often unfeasible or unethical to conduct experiments on real circumstances (field experiments on the road) because it would compromise the safety of the participants, researchers have two alternative methods to use. They involve either examining databases of past crashes and analyzing the effect of risk factors on them (which sometimes leads to lack of data), or conducting simulation experiments, which are in a controlled virtual environment where no hazard is present. There is also the option of naturalistic studies, which would have to involve the risk factor under examination (IVIS and device operation in the current case) and which require considerably more time and resources.

As for the analytic part, the binary approach is the most common method, which categorizes drivers as exposed or not exposed to each risk factor. There have also been more detailed approaches, such as studies that differentiate between physically interacting with the devices and solely browsing the screens.

3. Data and methods

3.1. Meta-analysis techniques

Meta-analyses are used as a tool to meaningfully summarize research results in a concise and comprehensive manner. The inverse-variance technique is commonly utilized by assigning to each risk estimate a statistical weight proportional to its sampling variance. The summary estimate of risk or effect based on g individual estimates is:

$$\text{Summary mean} = \overline{Y} = \frac{\sum_{i=1}^{g} Y_i * W_i}{\sum_{i=1}^{g} W_i} \quad (1)$$

where $\overline{Y}$ is the estimate of the weighted summary mean, based on g individual estimates, each of which is assigned a statistical weight W:

$$W = \frac{1}{SE_i^2} \quad (2)$$

The inverse-variance technique relates to two methods, which are (i) the fixed effects model and (ii) the random effects model. In fixed effects meta-analyses, if $i = 1, \ldots, n$ are independent effect size estimates, the true effect θ_i is the (unknown) true effect, and ε_i is the corresponding sampling error, y_i is the observed effect in the i-th study and is given as follows:

$$y_i = \theta_i + \varepsilon_i \quad (3)$$

Random effects meta-analyses are used to account for potential heterogeneity. The true effect θ_i has the components of u_i and μ. The parameter u_i follows a normal distribution with mean value μ and variance τ^2. If τ^2 equals zero, then the true effects are assumed to be homogenous (i.e. $\theta_1 = \theta_2 = \ldots = \theta_n = 0$).

$$\theta_i = u_i + \mu \tag{4}$$

The random effects model is more general in scope as it assumes systematic variation of results between studies, while the fixed effects model assumes one true effect and only sampling variation between studies. In simpler terms, a random effects analysis would report the true effect from a larger universe of observations using input studies as basis, while a fixed-effects analysis would provide the overall estimate based strictly on input studies. Additionally, the Q statistical test is performed to determine whether there is systematic between-study variation in results, where:

$$Q = \sum_{i=1}^{g} W_i * Y_i^2 - \frac{\left(\sum_{i=1}^{g} W_i * Y_i\right)^2}{\sum_{i=1}^{g} W_i} \tag{5}$$

More details on the theoretical background can be found in several papers [38–41]. For a more comprehensive paradigm of applying this meta-analysis methodology to a transport-related research topic the reader is referred to Theofilatos et al. [42] and Papadimitriou and Theofilatos [43]. The reader is additionally referred to Elvik [44], who provides an introductory overview of carrying out meta-analyses and to Elvik [45] who illustrates issues arising when studies are few and subpar when performing a meta-analysis. There have also been other meta-analyses considering driver distraction factors: Caird et al. [46] conducted a meta-analysis on driving performance and cellphones, and primarily concluded that cellphone use increases reaction times to events. Similarly, Caird et al. [47] meta-analyzed the effects of texting while driving from experimental studies and discovered an array of negative impacts while Caird et al. [48] used meta-analysis to acquire several comprehensive estimates of simulator or naturalistic driving results on distraction.

Furthermore, Viechtbauer [49] proposes the raw proportion and other configurations such as the logit transformed proportion as useful outcome measures when conducting a meta-analysis. It is stated that they are used when studies provide data for single groups with respect to a dichotomous dependent variable; this is the case for the impact of operating devices on road safety based on the reviewed studies. More specifically, in our selected studies, the "dependent variable" consisted of two values:

- Events of interest (crashes due to IVIS distraction)
- Total sample of events (all crashes)

Viechtbauer also notes that all the observations are assumed to be independent for the calculation (that is to say, participants contribute data only once when calculating the observed outcomes).

Initially, it was planned to carry out a meta-analysis on the odds ratios, as this would be even more informative. However, this approach was not feasible due to lack of sufficient number of studies. Thus, it

Table 1
Description of studies included in the meta-analyses.

No.	Author(s); year; country;	Sampling frame for studying operating devices	Parameter for impact investigation	Outcome indicators obtained	Main results
1	Dingus, T. A., Klauer, S. G., Neale, V. L., Petersen, A., Lee, S. E., Sudweeks, J. D., … & Bucher, C.; 2006; U.S.A.	This report presents the results of the field test of the 100-car naturalistic study. 100 vehicles were instrumented and monitored for about 12 months	Absolute (raw) proportion	Number of crashes (due to devices and study total)	Considerable amounts of data were recorded. 80% of crashes involved driver inattention from forward roadway. Crash underreporting was deduced. Zero crashes on device operation, however
2	Lansdown, T.C.; 2012; United Kingdom	Survey data were collected using an anonymous online questionnaire. 482 respondents contributed to the survey during a 2 month data collection period	Absolute (raw) proportion	Number of crashes (due to devices and study total)	Drivers are repeatedly conducting highly distracting tasks while driving. While proportion results are lacking statistical analysis to back this, regression models later in the study support it
3	McEvoy, S. P., Stevenson, M. R., & Woodward, M.; 2007; Australia	1367 drivers who attended hospital following a crash were interviewed. A questionnaire was administered to each driver and additional data were collected from ambulance and medical records	Absolute (raw) proportion	Number of crashes (due to devices and study total)	Judging by the percentages, adjusting in-vehicle equipment is a minor factor on relevant crashes, being one of the rarest
4	Neyens, D. M., & Boyle, L. N.; 2007; USA	Data from the US General Estimates System from the year 2003 were used for the analysis	Absolute (raw) proportion	Number of crashes (due to devices and study total)	Passenger-related distractions appeared more commonly than cell phone ones, and for teen drivers increased the likelihood of rear-end collisions
5	Stutts, J. C., Reinfurt, D. W., Staplin, L., & Rodgman, E. A.; 2001; USA	The Crashworthiness Data System (CDS) was employed to obtain more in-depth information on driver distraction related crash causes, including various distractions. 1995–1999 CDS data were used	Absolute (raw) proportion	Number of crashes (due to devices and study total)	Percentages show that device operations is a somewhat frequent factor on distraction crashes
6	Wang, J. S., Knipling, R. R., & Goodman, M. J.; 1996; USA	The Crashworthiness Data System was used to obtain more in-depth information on driver inattention related crash causes, including various distractions. This research paper reports the results of the 1995 CDS data collection	Absolute (raw) proportion	Number of crashes (due to devices and study total)	Judging by the percentages, inattention is a major factor on relevant crashes, followed by fatigue and out-of-vehicle distractions
7	Hanowski, R. J., Perez, M. A., & Dingus, T. A.; 2005; USA	Crash, near-crash, and crash-relevant conflict data from 41 long-haul truck drivers were examined	Absolute (raw) proportion	Number of safety-critical events (due to devices and study total) for professional drivers	Some drivers were disproportionately more distracted. Frequency and duration and visual demand of a task were found to contribute in combination to prevalence of critical incidents
8	Olson, R. L., Hanowski, R. J., Hickman, J. S., & Bocanegra, J. L.; 2009; USA	Data from two naturalistic studies were combined: 203 CMV drivers and 55 trucks. A total of 4452 safety-critical events were identified in the data set	Absolute (raw) proportion	Number of safety-critical events (due to devices and study total) for professional drivers	Drivers were engaged in non-driving related tasks in 71% of crashes. Performing highly complex tasks while driving lead to a significant increase in risk

Table 2
Summary of random effects meta-analysis estimates of operating devices on absolute proportion of all crashes.

Variable	Unit	Estimate	Std. error	p-value	95% CI
Operating devices (IVIS etc.)	Absolute proportion of crashes	0.0166	0.0044	0.0002	(0.0079, 0.0253)

was decided to utilize the proportions, which can be considered as a good alternative. This is an appropriate method, since an odds ratio cannot be calculated unless there is a 2 × 2 contingency table with an experimental group and a control group. There is currently a lack of studies reporting such numbers for IVIS in the literature, which indicates research gaps.

To enhance understanding of IVIS distraction, we also carried out a meta-analysis on the transformed proportions as suggested by Miller [50] who states that it is usually advantageous to transform the proportions into a measure that has better statistical properties (i.e., a sampling distribution that is closer to a normal distribution and whose sampling variance can be better approximated). Therefore, if x_i is the number of crashes influenced by IVIS operation, and n_i is the total number of crashes, the logit transformed proportion can be explored, namely $\ln[x_i/(n_i - x_i)]$. Thus, this parameter expresses the log-odds of crashes influenced by IVIS operation to crashes not influenced by IVIS operation, and it is the parameter of interest for the second meta-analysis.

Lastly, another core part of a meta-analysis is a funnel plot which is a tool used to visualize results of exploratory meta-analyses and are also helpful to detect potential publication bias, i.e. a tendency of not publishing findings which are not statistically significant or go against a-priori expectations of researchers [38]. Therefore, if studies with non-significant or small effects remain unpublished, an asymmetric funnel plot will be generated [51,52].

3.2. Study selection criteria

Following the literature review that was conducted, and in order to select studies to serve as candidates for potential inclusion in the meta-analysis, several selection criteria were applied. These criteria were developed in more detail within the SafetyCube research project [53]:

- Studies with quantitative findings and statistical models reporting standard errors were highly sought after.
- The number or severity of crashes were preferred over other indirect road safety outcome indicators (e.g. speed measurements).
- Recent and high quality studies reporting estimates of the examined effects were prioritized. More specifically, only recent papers (after 1990) in the fields of Engineering and Psychology were initially considered.
- Journal papers were preferred over conference papers. However, highly informative conference papers were included when necessary.
- High quality technical reports were decided to be included to improve source variety and increase the scope of this research after the first round of analysis.
- No "grey" literature (such as government reports, newsletters, lecture notes, presentations etc.) was included.

The references list of each study was also assessed to find relevant studies that may have not be found during the initial searching. A title and abstract screening was first implemented to identify the relevant studies. It is noted that the final group of studies eligible for full-text screening was 44. The final group of selected studies, along with the results, is described in the following section.

4. Results

4.1. Qualitative assessment of studies

After the application of the aforementioned criteria, the raw proportion of crashes due to operating devices was selected as the indicator to be considered for meta-analysis. It became apparent that the raw proportion parameter was the most frequently reported across the literature (or the most easily inferred based on data that studies report). Since the value of meta-analysis lies in the synthesis of various data sources, aiming for the raw proportion of crashes builds on that strength. Therefore studies reporting it were collected for conducting a meta-analysis; six studies were eligible for a general crash proportion meta-analysis and an additional two for safety-critical incidents for professional drivers.

It should be noted that several studies examining crashes were of good quality but had to be excluded for various other reasons; for instance Green [15] only reports casualties while in Stevens and Minton [16] only fatal crashes are reported. Ultimately, the studies considered were the following, with one estimate obtained from each of them. All studies have been described in the literature overview as well:

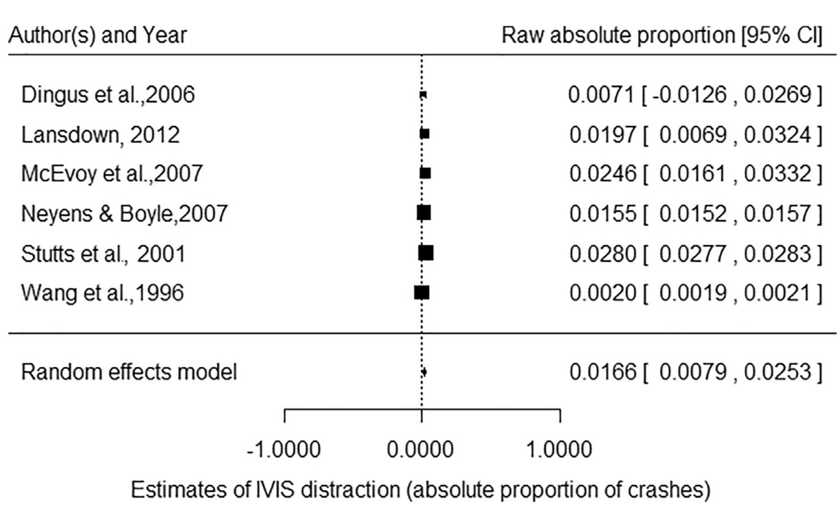

Fig. 1. Forest plot for the absolute proportion of total crashes that occur due to operating devices while driving.

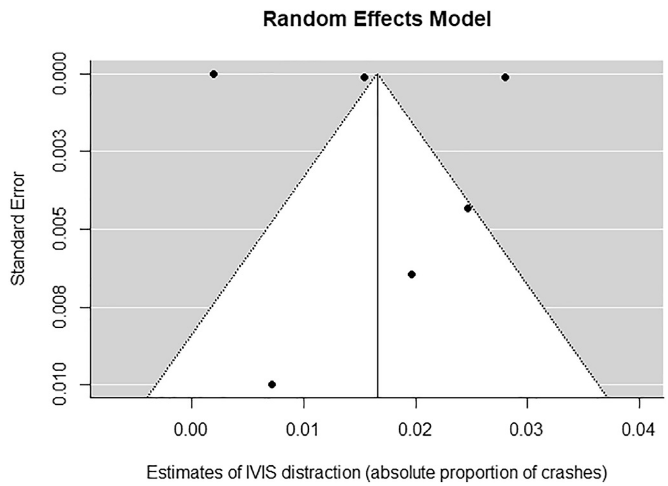

Fig. 2. Funnel plot for the absolute proportion of total crashes that occur due to IVIS distraction while driving.

1. Dingus et al. [10]
2. Lansdown [24]
3. McEvoy et al. [18]
4. Neyens and Boyle [21]
5. Stutts et al. [17]
6. Wang et al. [14]

From the review of the literature it was additionally determined that two studies were considering professional drivers (long-haul truck drivers and general commercial vehicle drivers, respectively). Both studies used similar parameters (safety-critical incidents/events). Since professional drivers are much more exposed to operating in-vehicle information devices, and also many more such devices are constantly developed for professional use, it was decided to attempt to meta-analyze the results of these two studies exclusively:

7. Hanowski et al. [22]
8. Olson et al. [23]

The results of the assessment of the included studies are summarized on Table 1:

4.2. Meta-analyses results

4.2.1. Raw and transformed proportions of number of crashes due to IVIS distraction

Since significant systematic variation is assumed across studies (and not just variation on a sampling level), it was initially decided to apply a random effects meta-analysis for the effect of operating devices while driving on crash numbers. More specifically, the overall estimate of the raw proportion of crashes due to operating device use was determined as a variable eligible for investigation. To do so, the number of crashes due to operating devices (x_i) as well the total number of crashes (n_i) were determined from each study (or calculated from reported percentages). Subsequently, the Q test for heterogeneity is used for every meta-analysis to test whether the implementation of random-effects model is correct, or a fixed effects model must be used instead.

Following Viechtbauer [49], the R-software [54] with the 'metafor' package was used to conduct the meta-analyses using the aforementioned studies as data input. Results of the random-effects meta-analysis indicate that the overall estimate of the effect of operating in-vehicle information devices on the absolute proportion of crashes is 0.0166 (with 0.0044 standard error), and the 95% confidence intervals are 0.0079, and 0.0253 respectively, as shown on Table 2 and Fig. 1, which also depicts the average contribution of each study to the analysis (individual observed effect sizes). The *p*-value (0.0002) indicates a statistically significant effect at the 95% level.

In simple terms, the analysis conducted shows that about 1.66% of the total crashes that occur are due to operating in-vehicle information devices.

The Q test is significant ($Q_{[df=5]} = 45384.4454$, p-value < 0.001), hinting at considerable heterogeneity for the true effects. This supports the implementation of the random effects model as opposed to using a fixed effects meta-analysis. A funnel plot and respective testing were also conducted to detect possible publication bias and appears on Fig. 2 that follows. The regression test for funnel plot asymmetry was not significant at the 95% level ($t = -0.057$, p-value $= 0.9545$), indicating that correction for publication bias is not required. Moreover, no correlation between observed outcomes and standard errors were found as well (p-value $= 0.9545$). It would appear that most results were reported in studies considered, and no results remained unpublished due to them being counterintuitive or unexpected.

Similarly, the overall estimate when using the logit transformation of raw proportions was extracted. The results of the random-effects meta-analysis indicate that the overall estimate of the effect of operating in-vehicle information devices on the log odds of crashes is −4.3537 (with 0.4609 standard error), and the 95% confidence intervals are −5.2570, and −3.4503 respectively, as shown on Table 3 and Fig. 2, which also depicts the average contribution of each study to the analysis (individual observed effect sizes). The *p*-value (<0.0001) indicates a statistically significant effect at the 95% level.

Afterwards, in order to produce interpretable results, the log odds obtained from the logit transformed proportion had to be transformed back by using the exponential of the result. Consequently, the odds of crashes due to IVIS distraction were $\exp(-4.3537) = 0.0129$. This indicates that the odds of crashes influenced by IVIS operation are 0.0129, a very low number which is however intuitive.

Fig. 3 illustrates the respective funnel plot. In this case, the regression test for plot asymmetry and for correlation between observed outcomes and standard errors was insignificant as previously (p-value $= 0.9327$).

4.2.2. Raw and transformed proportions of number of incidents due to IVIS distraction to professional drivers

As explained previously, it was also attempted to conduct a separate meta-analysis for professional drivers from a sample of two studies, this time using incidents instead of crashes. When trying to apply a random effects model, it was found that the Q test was not significant ($Q = 2.1216$, p-value $= 0.1452$). Therefore not enough heterogeneity is observed among the true effects based on these two studies. Thus a fixed-effects meta-analysis is resorted to, with the limitations it contains as described in section 4.1.

Results of the fixed effects model indicate that overall estimate of the effect of operating in-vehicle information devices on the absolute proportion of incidents is 0.0061 (with 0.0005 standard error), and the 95% confidence intervals are 0.0052, and 0.0070 respectively. The *p*-value (<0.001) indicates a significant effect at the 95% level as shown on Table 4.

In simple terms, the analysis conducted shows that 0.61% of the total safety-critical incidents that involve professional drivers are due to

Table 3
Summary of random effects meta-analysis estimates of operating devices on log odds of all crashes.

Variable	Unit	Estimate	Std. error	*p*-value	95% CI
Operating devices (IVIS etc.)	Log odds of crashes influenced by IVIS	−4.3537	0.4609	<0.0001	(−5.2570, −3.4503)

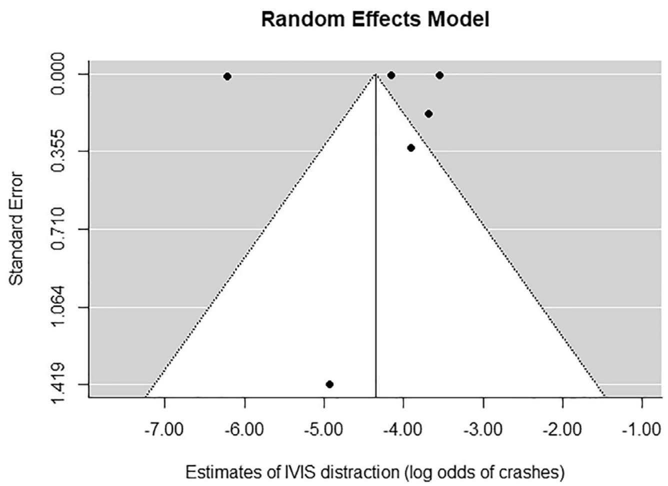

Fig. 3. Funnel plot for the proportion of crashes that occur due to IVIS distraction while driving (logit transformation).

operating in-vehicle information devices. This does seem like a minor percentage given other risk factors such as cellphone use.

Table 5 illustrates the log odds of incidents. In order to produce interpretable results, the log odds had to be transformed again by using the exponential ($\exp(-5.0771) = 0.0062$). Consequently, it is indicated that the odds of safety-critical incidents influenced by IVIS operation is remarkably lower for professional drivers than the odds of crash occurrence influenced by IVIS for the general population of drivers (0.0062 compared to 0.0126).

At this point it should be noted that since these results are based on a small sample, they should be treated with significant caution. Due to the very small number of studies, it was decided that it was not meaningful to test for publication bias, as the symmetry of the plot would not be discernible. A few studies in the past also attempted to carry out meta-analyses with only a limited study sample [55]. In practice, they should be better treated as an indication of the trend, probably requiring more studies to reveal more concrete outcomes.

5. Discussion

5.1. Study findings

This paper conducted a selective review of the current literature on operating in-vehicle devices with the explicit purpose of determining their effects on road safety. It was determined that the exact impact of device operation was not clear, with some cases of studies finding a non-significant effect and others a more considerable one. In an effort to provide a more well-rounded approach, certain studies were selected with the intent of conducting relevant meta-analysis, thus endeavoring to obtain an overall estimate.

The parameter that was determined appropriate for examination was the total absolute crash proportion for crashes caused by operating devices. Analyses results show that operating devices cause 1.66% of the total crashes (std. error = 0.0044), and indicate a number of 0.61% of the total safety-critical incidents for professional drivers (std. error = 0.0005). Alternatively, it was found that the odds of crashes influenced by IVIS operation is 0.0129.

Considering total crashes, 1.66% is a small percentage compared to that of other risk factors (such as cellphone use); this finding is in line with results of in-depth crash investigation studies (e.g. a study from UK DfT [56]) and it is not negligible given absolute crash numbers in motorized countries with modernized vehicle fleets that include in-vehicle devices. Moreover, the penetration of such systems is expected to further increase as expected by relevant research [12,57] and therefore monitoring of their contribution to distraction-related crash occurrence is critical.

The second result (presence of IVIS in 0.61% of the total safety-critical incidents) appears more negligible in the greater picture of device integration for professionals, hinting perhaps at successful device design developments thus far. Alternatively, it was also found that the odds of safety-critical incidents influenced by IVIS operation is 0.0062. However, the second meta-analysis (which regards to professionals) has reduced transferability due to very limited study sample, and is best treated as an indication.

As has been often the case [49], the meta-analysis process is useful to concisely express the results of several different previous studies. The random effects meta-analytic approach implemented in this study considers these studies samples of a greater whole and produces results to accommodate for unobserved heterogeneity. There are limitations to the study, as discussed in the following.

5.2. Study limitations

Reflecting on the approach undertaken, it is evident that for the purposes of conducting meta-analyses there are considerable margins for studies examining and reporting the proportional impact of device operation on crashes or safety-critical events.

Several reasons could possibly exist for this limitation. Firstly, there is a multitude of IVIS and other similar devices available for implementation, with more being constantly circulated commercially. For their exact assessment establishing a taxonomy of devices and studying their road safety impact based on that taxonomy is a considerable task on itself. After this step it would be possible to conduct meta-analyses in behavioral variables such as lane-keeping or glance behavior.

Secondly, quite often studies currently available integrated operating devices with other in-vehicle distraction categories such as cellphone use, conversation with passengers or consumption of goods, perhaps due to its relatively decreased appearance frequency compared to these categories. Cellphones have especially dominated researcher interests, leading to relatively few studies for other types of devices (such as [58]). Thus the need of more specialized and dedicated studies for device operation becomes apparent, especially in the case of systems of increased complexity and cognitive demands. Interestingly, when examining road safety measures in particular, even studies examining dedicated IVIS safety measures might be inconclusive at times (such as [59]).

Moreover, there is a limitation regarding the sample size. Although, it is sufficient to carry out a meta-analysis (at least for the first analysis which involved crashes), it could not enable to carry out a meta-regression, which would add more to the understanding of this issue. However, some studies have also utilized a meta-analysis with fewer studies (e.g. Roshandel et al. [55]) in order to exploit this very useful analytical tool and gain insights.

Lastly, some of the initial studies were in the state of things of past decades, with older crash data; effectively this meant that device operation was not as widespread then as it became more recently. On the other hand, studies which were conducted more recently benefited from technological advances such as better simulators and instrumentation that enabled tracking of finer behavioral variables (such as eye

Table 4
Summary of random effects meta-analysis estimates of IVIS distraction on absolute proportion of all incidents for professional drivers.

Variable	Unit	Estimate	Std. error	*p*-value	95% CI
Operating devices (IVIS etc.)	Absolute proportion of incidents	0. 0061	0.0005	<0.001	(0.0052, 0.0070)

Table 5
Summary of random effects meta-analysis estimates of IVIS distraction on log odds of all incidents for professional drivers.

Variable	Unit	Estimate	Std. error	*p*-value	95% CI
Operating devices (IVIS etc.)	Log odds of incidents influenced by IVIS	−5.0771	0.0776	<0.001	(−5.22, −4.92)

movement indicators) and somewhat disregarding crashes or safety-critical events.

Additionally, studies included in the meta-analysis originate mainly from the USA, and only the UK and Australia are also represented with one study each. While this is a decent dispersion sample for motorized countries, once again there is room for improvement of the remaining areas of the globe. Another aspect with margins for improvement would be the field of Cost-Benefit Analysis for the increasing benefits of more safe and driver-friendly in-vehicle systems.

5.3. Practical applications

The numerical results from the presented meta-analyses can be used to quantitatively rank any IVIS-related countermeasures research. Using them as input in a Cost-Benefit Analysis practitioners can meaningfully prioritize resource expenditures with the knowledge of the amount of the target crash population (and derive possible reductions).

Finally, it should be noted that while the topic of in-vehicle information systems might not seem currently as the top priority for road safety, it might become considerably pertinent with the arrival of connected and autonomous vehicles. In moderate levels of automation there are going to be distraction issues when drivers are called to resume manual driving from automated navigation, as has been already explored in the literature [60,61,]. In that light, the value of the current research increases as it summarizes concisely the current effect of in-vehicle systems on crashes for conventional vehicles, before Connected or Automated vehicle technology is implemented.

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