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Observing the observation of (vulnerable) road user behaviour and traffic safety: a scoping review

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Observing the observation of (vulnerable) road user behaviour and traffic safety: a scoping review

Behavioural observation studies in road safety research collect naturalistic data of road users that are not informed (beforehand) of their participation in a research project. It enables the observation of behavioural and situational processes that contribute to unsafe traffic events, while possible behavioural adaptations due to the road users' recognition of being observed are minimized. The literature in this field is vast and diverse, with studies dating back to the 1930s. The aim of this paper is to summarize the research efforts in the domain of road user behavioural observation research to examine trends and developments of this type of research, using a scoping review. After the definition of certain selection criteria, 600 journal articles found in three major online databases were retrieved and included in this review.

The number of publications regarding road user behavioural observation studies has increased rapidly during recent years, indicating the importance of behavioural observation studies to study traffic safety. Most studies collected data on car drivers (81%), while vulnerable road users have been observed in 32% of all studies, with pedestrians and (motor)cyclists as the most common road user types. The results showed that the main goal of behavioural observation is to monitor (51%), followed by the evaluation of a specific safety improving measure (38%) and the development of behavioural models (10%). Most topics relate to traffic events where interactions with other road users are necessary, indicating that the examination of behavioural processes underlying single-vehicle crashes has received little attention. The ongoing developments of automated video analysis software tools can be the next methodological step forward in video-based behavioural observation studies, since it enables a more objective data collection and data analysis process.

Keywords: behavioural observation; behavioural indicators; scoping review; traffic safety; vulnerable road users

1. Introduction

Road safety literature has identified road user behaviour as a key aspect of road safety, which plays an important role in the complex interactions between road users, the vehicle and the environment (Polders, Van Haperen and Brijs, 2018, p127). Several studies highlight the importance of examining road user behaviour, since it is in 94 % of all crashes a contributing factor, while the environment and the vehicle are partly responsible in 18 % and 8 % of all crashes (Reason, 2000; Sabey and Taylor, 1980; Treat et al., 1979). However, crash data usually lacks information on behavioural aspects (e.g. Laureshyn, 2010). Therefore, several traffic safety evaluation methodologies that do not rely on crash data have been proposed and applied in the scientific literature. These approaches focus on both dangerous situations and actual crashes, either in real world or hypothetical traffic situations. According to Shinar (1998), research methodologies for evaluating traffic safety are either experimental or observational. In experimental research, one can manipulate traffic conditions to trigger events of interest (e.g. in a simulation) or question participants about what they would do when confronted with a certain situation (e.g. in interviews). For observational research, on the other hand, researchers are dependent on the behaviours that are shown in real-world environments by users or test subjects under observation. Table 1 provides an overview of these different approaches, including some concrete examples of methodologies.

Table 1 The most common safety evaluation methods used in scientific literature.

Observational		Experimental	
Reported	Observed	Simulated	Interviewed
Crash data	Naturalistic Driving	Driving Simulator	Questionnaires
	Behavioural Observation*	Microsimulation	Interviews
	Traffic conflict observation	Virtual reality	Focus groups

* focus of this scoping review

Observational studies collect naturalistic data in settings in which the road user behaviour of interest occurs (Eby, 2011). There is no control over the traffic situations that participants will encounter. Several methodologies have been used to observe behaviour. Naturalistic driving techniques use instrumented vehicles to collect detailed behavioural data of its driver, but participants are usually aware that they are part of a research experiment (e.g. Pariota & Bifulco, 2015). This review focuses solely on behavioural observation studies in which the road user is not informed (beforehand and usually not afterwards either) about participation in the research project. This is an important difference, because natural settings in which road users are unaware of being observed reduce bias caused by behavioural adaptation effects (i.e. changing one's behaviour when one knows one is being observed) and increase the likelihood to observe the whole diversity of behaviours, including risky and aggressive driving behaviours (Shinar, 1998). Although it cannot be guaranteed that road users passing the observation site remain unaware that road user behaviour is been monitored, it is not likely that they have time enough to adapt their behaviour, if they would like to do so, once the observing equipment (e.g. human observers or cameras) has been detected. Furthermore, behavioural observation studies capture the behaviour of all the road users passing the observation site, while naturalistic driving studies continuously observe selected participants. A special form of behavioural observation studies is traffic conflict observation, which has the specific aim to measure traffic safety in terms of the expected number of crashes. These studies were not included in this review, but have been the topic of another scoping review (Johnsson, et al., 2018)

The scientific literature in the field of road user behavioural observation studies is vast and diverse, with publications dating back to the 1930s. This study sets out to summarize these research efforts to examine trends and developments that are important for future research efforts. Studies that focus directly or indirectly on road safety aspects using road user behavioural observation techniques are included in this scoping review.

2. Methodology

Scoping reviews are a means to "map rapidly the key concepts underpinning a research area and the main sources and types of evidence available" (Mays, & Roberts, & Popay, 2001). They are highly effective in research areas that are not reviewed comprehensively before. Such reviews can be used for many applications, even outside the authors' intended purposes (Armstrong & Hall, & Doyle, & Waters, 2011) and that guiding future research and reducing duplicate efforts are important additional objectives (Wee & Banister, 2016). An important strength of a scoping review is that a systematic literature retrieval process, based on a search protocol, is used, which provides transparency to the reader of the review. This is not the case with narrative literature reviews, in which implicit processes are used to provide evidence that reinforces the ideas and research objectives of the author (Garg, & Hackam, & Tonelli, 2008). With such studies, the reader cannot determine if the evidence presented is based on the author's experience, how extensively the literature was searched for and if specific studies were ignored due to contradicting findings (Van Haperen, 2016). A scoping review is also very useful when the research aim does not focus on a specific issue (e.g. the effectiveness of a certain traffic safety improving measure), but examines the extent, range and nature of research activities within a particular research domain. The main difference with a systematic review is that for scoping reviews the research question is rather broad and that the quality of the retrieved evidence is generally not evaluated (Dijkers, 2015). To describe the exact focus of this study, the following key-concepts are defined (Van Haperen, 2016):

- Road users are all users of the road infrastructure that can move freely and are not constraint to guiding systems (e.g. trains on rails). Transportation modes that are guided are excluded because drivers/riders of those modes have limited control over their direction.
- Safety is the absence of possible unintended harm to road users or damage to the vehicle of their mode of transportation (based on Evans (2004, p6)).
- Behavioural observation studies are studies observing the behaviour of road users, in which the observed road users are not informed (beforehand) of their participation into the research project. These studies focus on how road users pass the observation site and should be related to traffic safety. Traffic conflict studies fit that definition, but will not be covered in this review as stated in the introduction.
- Vulnerable road users (VRUs) are those road users that do not have a protective shell around them (Wegman & Aarts, 2006). Those road users include, among others, pedestrians, cyclists and motorcyclists.

This paper builds on the findings published in Van Haperen (2016). Therefore, it makes use of the same methodology and literature selection processes that are described in the following sections. For more information, readers are referred to the Van Haperen (2016) report.

2.1 Search Protocol

A search protocol was created, which included information on the databases searched, the search terms used and the in- and exclusion criteria applied. After testing several combinations, the search term "*Traffic AND (Behavio*r OR Safety)*" was used in the online databases Web of Science, ScienceDirect and TRID (Van Haperen, 2016). Only studies published in English in peer-reviewed journals were included. Publications up to and including 2015 were retrieved. The databases identified 21.243 references, which were all imported into the Endnote referencing software (2015). After the automatic and manual removal of duplicate entries, 12.188 references remained for screening.

2.2 Screening

As can be seen in Figure 1, three rounds of screening were used by the review team, consisting of two members, to identify eligible references. The first screening round focused on excluding all studies that were not peer-reviewed journal articles published in English. Afterwards, both reviewers evaluated the title and abstract of each reference to determine the relevance of the remaining 7.072 entries. Different decisions were discussed between the members of the research team and if no consensus was reached, the reference was kept for the final round of screening. During this final stage, full-text articles were read and relevant information was extracted and stored into a codebook, programmed in Microsoft Access (2015). Each article was coded by both reviewers until a satisfactory level of coding consistency (> 90 % of identical coding per paper) was reached, minimizing coding bias. Additionally, a subsample of papers was coded by both review members during the entire process to continue testing coding consistency. Whenever a reviewer was not sure about certain aspects of the extracted information or if an article did not seem to be eligible for information extraction, a notation was made and the references was fully checked by the other review member as well (Van Haperen, 2016).

The automatic text retrieval function in Endnote was used to retrieve the full-text articles. Articles that could not be found automatically were searched for manually through Google Scholar and Research Gate. Also, a list of missing articles was created and sent to several international partners. Finally, the library services of Hasselt University were consulted for trying to acquire missing articles. In total, 23 articles that are potentially relevant (3 %) could not be retrieved. A list of all references that were included in the review and a list of potential relevant journal articles can be found in Van Haperen (2016).

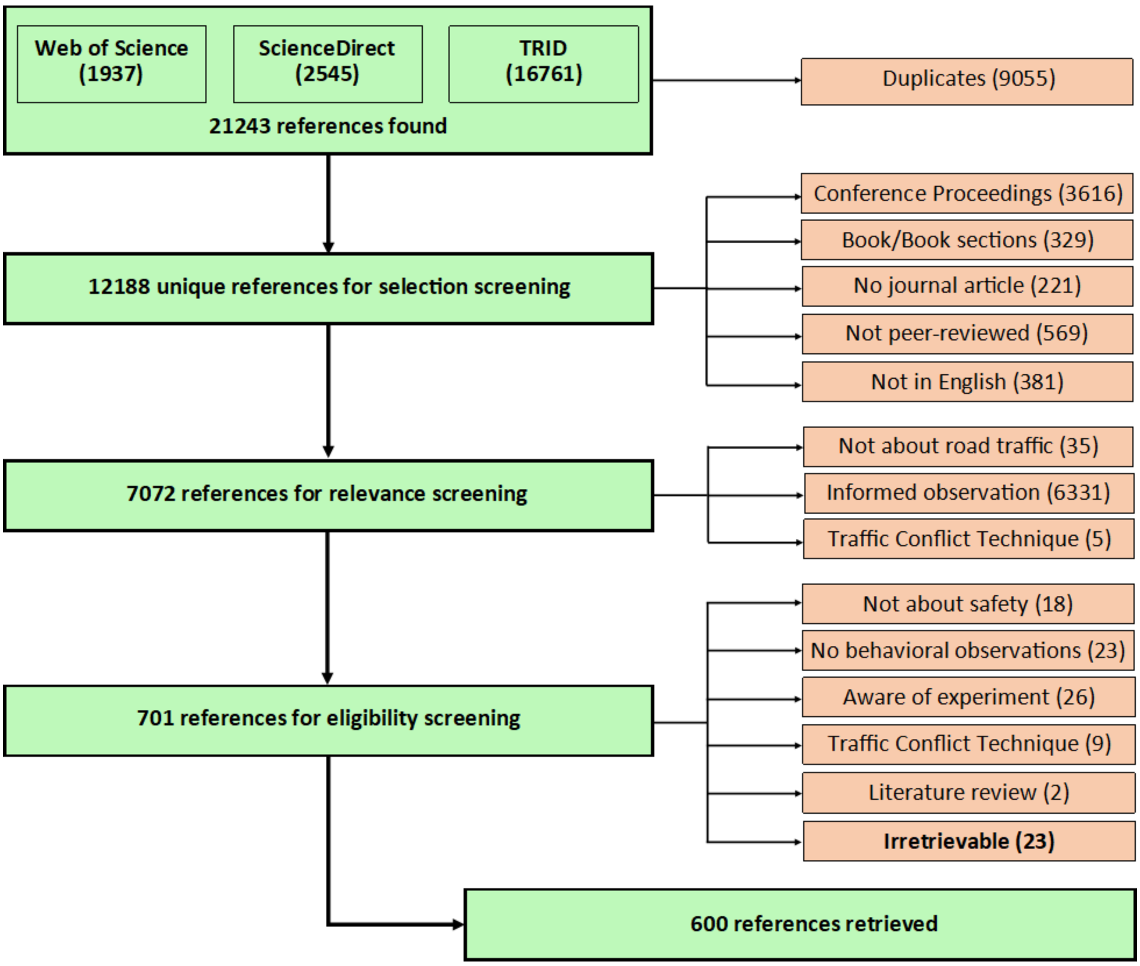

Figure 1 Flow diagram of the literature inclusion process.

3. Trends in road user behavioural observation research

Road user behavioural observation studies have been published in the scientific literature for almost 80 years, presenting a vast amount of diverse information. Appendix A provides a descriptive summary of the main findings, focusing on important study characteristics. More detailed information can be found elsewhere (Van Haperen, 2016), since the focus of this paper is to highlight important trends and developments that can be observed in the long history of road user behavioural observation studies. Information regarding study purposes, data collection processes, study characteristics and topics and indicators are discussed in the following sections.

3.1 Road user focus and number of publications

Around one third (n=193, 32 %) of all identified studies collected data on at least one VRU-type (from here on mentioned as VRU-studies), with the first study dating back to 1973. Of these studies, pedestrians have been observed most (70 %), followed by cyclists, including electric bikes and mopeds (28 %), and motorcyclists (14 %). Over 80 % (n=485, 81 %) of the studies collected data on at least one non-VRU-type (from here on mentioned as Driver-studies), with the first study dating back to 1939. Car drivers were included in all but one of these studies. Proportions of other road user types (e.g. buses and heavy good vehicles) could not be correctly identified, since authors have not always clearly stated which vehicle-types were included in their research. Certain studies (n=78, 13 %) have been categorized both as a VRU- and driver-study, since information of both road user categories was collected. Figure 2 provides an overview of the number of annual publications in the period 1935-2015, split into study type, including a line showing studies that belonged to both study types. The trend lines show an exponential increase in the number of publications during recent years, highlighting that during recent years more studies have been published. More than 70 % (n=343) of Driver-studies have been published since the 2000s, while almost 60 % (n=112) of all VRU-studies have been published during the 2010s. A clear peak in the number of Driver-studies can be observed during the early 1980s, possibly caused by the increased interest in evaluating the effectiveness of the implementation of mandatory seatbelt laws in the United States. As expected, the graphs further show that both VRU- and Driver-studies follow the same trend in terms of in- and decreasing number of publications between consecutive years from the 1990s onwards.

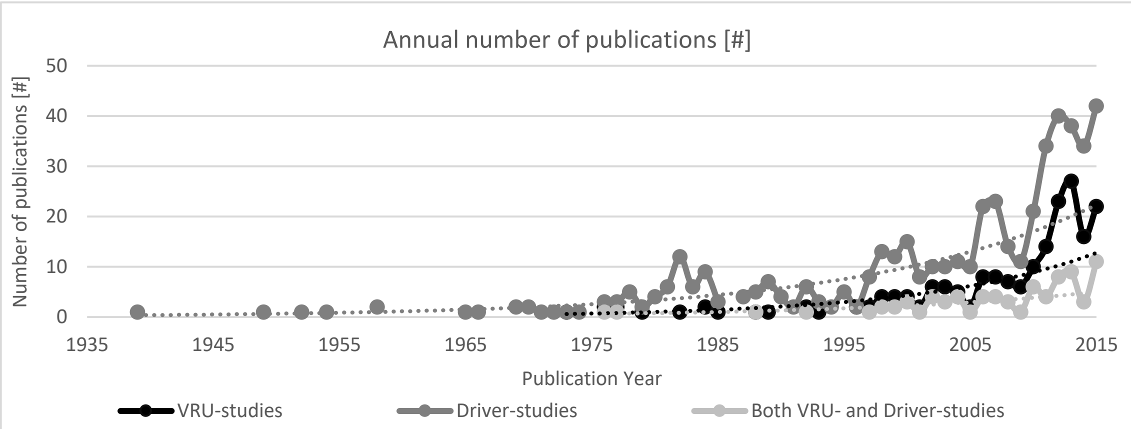

Figure 2 The annual amount of publication per study-type. The dotted line shows an exponential trend line. Note that certain studies are represented twice: as VRU- or driver study and both.

The increasing number of publications is in line with the results of Hagenzieker et al. (2014), who found that studies in the domain of road safety research in general have increased since 2000. Contributing factors to this increase are possibly that during the 1990s the field of road safety research moved towards “an increasingly scientific and cross-disciplinary phase” (OECD, 1997) and that the topic of road safety received more attention and recognition after the publication of the World Report on Road Traffic Injury Prevention of the WHO (Peden et al., 2004), in which road traffic fatalities were predicted to be the third leading cause of death worldwide by 2020. The fact that the increasing number of publications since 2000 in the domain of road safety research in general also applies to behavioural observation studies suggests that the latter are an important tool to study traffic safety.

3.2 Data collection

Figure 3 shows the use of the two most common data collection tools for road user behavioural observation studies. On-site human observers have been most often used for more than 60 years until the mid-2000s. They can collect data relatively quickly and efficiently, but the main criticism of using trained observers is that the data collection process is influenced by inter- and intra-coder reliability (e.g. Williams, 1981) and that there is a certain degree of subjectivity (Grayson, 1984). Furthermore, it can be very difficult to collect all data when multiple events occur simultaneously. These drawbacks become more important when the data collection process is more complex and when the measurements are based on estimations that cannot be verified afterwards (e.g. speed). The introduction of new data collection tools like video cameras, loop detectors and speed guns has enabled the more reliable and detailed measurements of behavioural indicators that are based on speed, distance and time. Finally, using human observers to collect and analyse data is a time consuming process with potentially high labor costs. The use of video cameras as primary data source has surpassed the use of direct human observations during the mid-2000s, the same period in which the number of publications started to increase rapidly. Even though most often human observers review the video data, the opportunity exists to repeat the entire data selection and analysis process. Other advantages of video cameras over on-site human observers are the possibilities to continuously collect data during longer periods of time, the opportunities to replay videos as many times as necessary to extract relevant information and that the videos provide an efficient means of communicating results to other researchers and stakeholders. Furthermore, the costs of using cameras has decreased due to their increased usage, making it more attractive to use them (St-Aubin, Saunier & Miranda-Moreno, 2015).

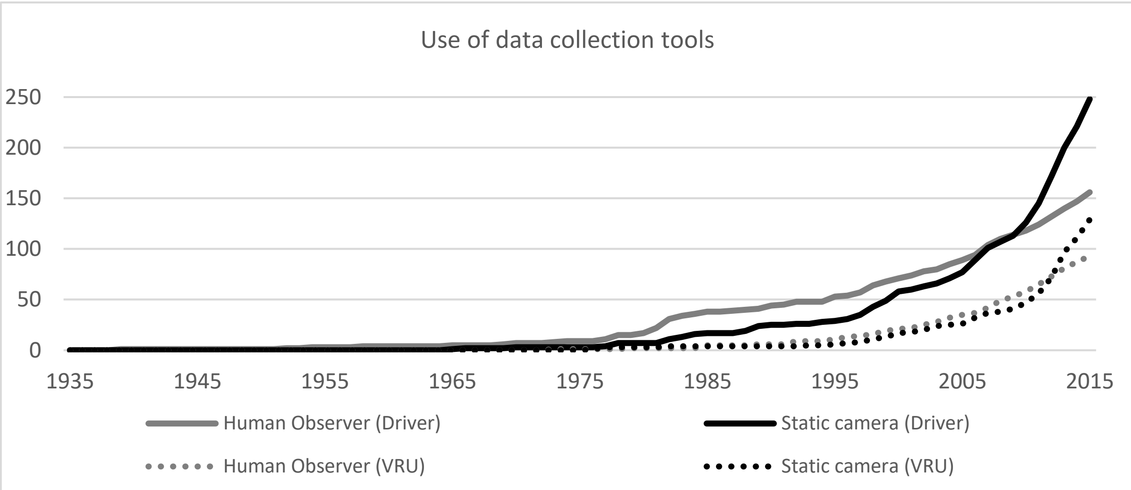

Figure 3 The use of the two most common data collection tools, split into road user category.

Given the fact the cameras are most often used during the data collection process nowadays, the development of automated video analysis tools is an area of active research with already promising results and may become the next methodological step forward for behavioural observation studies. First, fully functional tools will be able to collect and analyse video data in a completely objective manner, assuming that the algorithms created by humans are working properly. Secondly, the costs for analysing large datasets are reduced, since no human observers are needed to review the videos manually. Also, the analysis process can run continuously on the background. Finally, traffic cameras are becoming part of the road infrastructure system in many countries nowadays, so road users are likely to be used to them and not to adapt their driving behaviour after noticing one. Furthermore, the already installed cameras could be used to collect data for research purposes, avoiding additional costs for installing new ones.

Many researchers have already focused on the development of software tools that can (semi-)automatically analyse videos (e.g. T-Analyst (2017) and Traffic Intelligence (Jackson et al. 2013; Saunier, 2012)). Such research efforts were only found sporadically in this review (n=4), most likely because the developments of (semi-)automated video analysis software has not only potential for behavioural observation studies, but is also promising for all kinds of purposes, including traffic management, incident management and security in general. Technological problems (e.g. accuracy of identifying road users and their exact position) are not the only challenges for the development of automated video analysis software tools. The review suggests that privacy legislations limiting the possibilities to collect (personal) data can be an important issue. This is especially important if one is interested in inside-vehicle behaviour. Only two studies were found that positioned cameras in such a way that it was possible to look inside vehicles (Summala et al, 1996; Tenkink & Van der Horst, 1990) without the drivers' knowledge of being observed, but these publications are over 20 years old. Most often, trained human observers on-site are used to collect this type of data, with the drawback that the data needs to be collected and analysed manually. Other methodologies exist that can collect video data inside the vehicle (e.g. naturalistic driving), but in these cases the driver is usually aware of being observed. Privacy issues can also relate to outside-vehicle behaviour as well since cameras might record license plate numbers or even capture crashes on tape. These issues are typically not mentioned in published articles, but privacy legislations can potentially influence the decision whether or not to use video cameras as a data collection tool.

3.3 Research purpose

This review identified four main purposes of behaviour observation studies. These categories are exclusive and defined as follows:

- Monitoring: One location or multiple similar locations are observed to monitor the road user behaviour. The goal of such studies is to 'look what happens' and not to examine a certain intervention or safety improving measure. An example is the observation of the effect of mobile phones on pedestrians' crossing behaviour (Hatfield, & Murphy, 2007).
- Evaluation of certain safety improving measures: Using a before-after, with-without or cross-sectional research design, the effect of an infrastructural intervention or safety improving measure is evaluated (e.g. the evaluation of the impact of red light cameras on dilemma zone behaviour (Polders et al, 2015)).
- Model development: Real world data is used to develop/calibrate/validate behavioural models for simulation tools (e.g. microsimulation models), for example gap-acceptance models (e.g. Kadali, & Vedagiri, & Rathi, 2015).
- Automated video-analysis software development: Video data of traffic events is used to develop and test automated video-analysis tools (e.g. tracking algorithms and road user classification). In these cases, the behavioural observation serves as a case study to test the developed algorithms. An example is the study of Zaki & Sayed (2014) in which non-conforming pedestrian behaviour was observed.

Monitoring has been the main aim (around 51%), followed by the evaluation of a safety treatment (38%) and the development of behavioural models (10%). The same distribution of study purposes was found for both VRU- and driver-studies, indicating that the approaches towards examining VRU- and driver safety are similar. Figure 4 contains the research purposes per road user type over the years, to investigate if the purposes have remained constant over time. Only studies investigating drivers' behaviour during the 1980s and 1990s focused more on the evaluation of safety improving treatments rather than on monitoring. Furthermore, studies focusing on cyclists and the evaluation of safety improving treatments have been conducted mainly since 2010. Cyclists have rarely been included in model development studies. The only two studies found did not focus on cyclists specifically but on any road user type that passed the location of interest. Finally, it can be observed that the number of studies have increased over time for all research purposes for the four road user types.

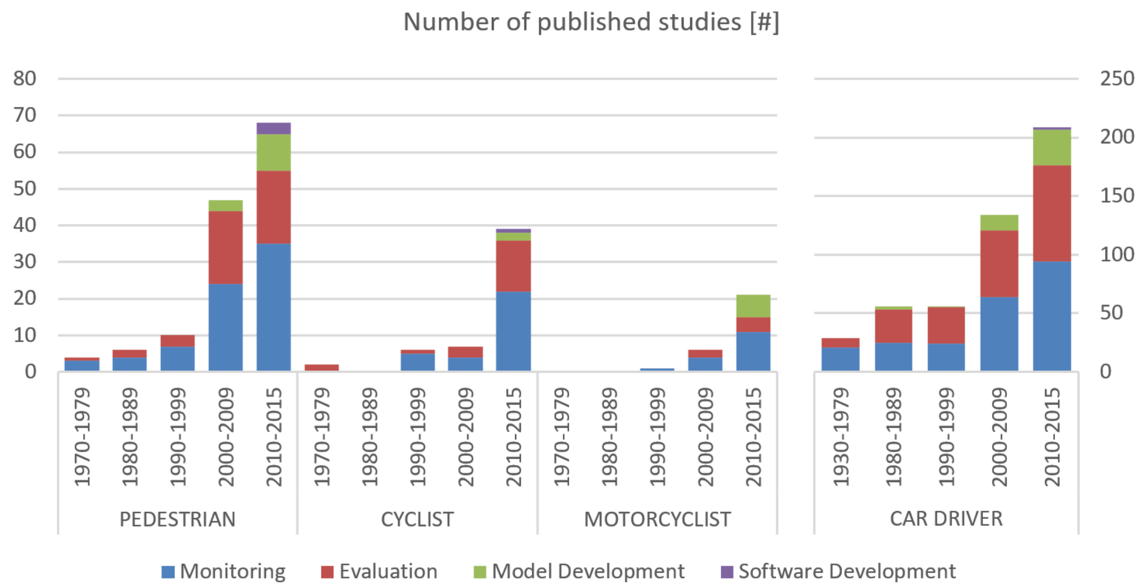

Figure 4 The number of publications, presented according to research purpose and publication year.

3.4 Topics and indicators

Behavioural processes targeted by behavioural observation studies were examined. To do so, two important steps were followed: first, titles and abstracts of the included studies were examined to determine the main topic and secondly, the full-text papers were accessed to identify which indicators were collected to draw conclusions. Following this procedure, we identified 24 research topics and 38 behavioural indicators. Indicators that related to aspects other than behaviour, for example personal characteristics like age, gender and ethnicity, were ignored. More information on the defined topics and indicators can be found in Van Haperen (2016).

3.4.1 Topics

Table 3 shows the categorization of the research topics, based on the three pillars of contributing crash factors, i.e. the road user, the vehicle and the infrastructure (Sabey and Taylor, 1980), to examine how these pillars are related to behaviour observations investigated in the literature. Most studies focused on topics that relate to interactions with other road users, both for VRU- and driver-studies (78 % and 68 % respectively). To further investigate these behavioural processes, a categorization of the types of interactions is used. The first category, direct interaction, is composed of situations in which two or more road users need to negotiate with each other and anticipate each other's actions, to pass each other safely. Examples are crossing and yielding behaviour, where direct communication between the road users involved is necessary. This type of behaviour has been researched most often, in the case of VRU-studies it even comprises 66 % of all retrieved publications. Secondly, an indirect interaction is defined as an event where a road user's behaviour is influenced by the presence of another road user, but where direct communication is not necessary. For example, during an overtaking manoeuvre the driver overtaking needs to interact with the driver that is being overtaken, but does not need to communicate with the other driver to safely start or finish the overtaking manoeuvre. Another example is car-following, where the driver following another vehicle needs to adapt his driving behaviour to the leading driver, but where the leading driver does not need to adapt his/her behaviour to the driver behind. Thirdly, a possible interaction is defined as an event where a road user's behaviour is not necessarily influenced by the presence, and may be more influenced by the absence of other road users (e.g. speeding).

The findings indicate that direct interactions have received most research attention, especially for VRUs. This may be because during these traffic events VRUs are at their most vulnerable. Furthermore, topics that were categorized in the other interaction categories are mostly not applicable to pedestrians and cyclists. When looking at driver studies, it can be observed that most research efforts have dealt with topics related to direct interactions (30 %), and that the topic of 'speeding' has received most attention (16 %). This finding may be explained by the fact that a microscopic relationship between average speed and crash risk has been proven (Elvik, & Christensen, & Amundsen, 2004).

Table 3 The types of behavioural topics, sorted on occurrence in VRU-studies. Between squared brackets are the occurrences in percentage for VRU- and driver-studies.

ROAD USER **[78% ; 68%]**	**VEHICLE** **[5% ; 12%]**	**ENVIRONMENT** **[17% ;12%]**
Direct interaction [66% ; 30%]	In-vehicle [2% ; 9%]	Circumstances [3% ; 6%]
Crossing [44% ; 11%] Yielding [18% ; 14%] Road sharing [3% ; 1%] Merging [1% ; 4%]	Protective clothing [2% ; 0%] Seatbelt [0% ; 7%] Child restraint [0% ; 1%] Turn indicator [0% ; 1%]	Shared space [2% ; 1%] Work zone safety [1% ; 3%] Weather conditions [0% ; 2%]
Indirect interaction [7% ; 15%]		Outside-vehicle devices [14% ; 8%]
Gap acceptance [3% ; 4%] Overtaking [2% ; 5%] Car-following [1% ; 4%]		Red-light running [10% ; 4%] Phase change warning [4% ; 3%] Emergency Vehicle Alert [0% ; 1%]

Lane change [1% ; 2%]		
Possible interaction [3% ; 20%]		
Speeding [2% ; 16%] Dilemma zone [1% ; 4%]		
Other [2% ; 3%]	Other [3% ; 3%]	
Risky driving [1% ; 2%] Violations [1% ; 1%]	Mobile phone [2% ; 2%] Other Distraction [1% ; 1%]	

Note: Few studies were identified as having two topics. Studies that could not be put into these categories are not included: hence, the percentages do not necessarily add up to 100%.

Finally, it was investigated if the topics that received most research attention changed over the years. Table 4 contains the top three research topics for VRU- and driver-studies per decade, starting at the decennium in which at least two studies investigated the same topic. It shows that VRU-studies mainly focused on locations where interactions with other road users is required, with crossing being examined most often. Yielding behaviour and red-light running are the other two topics that complete the top three of research topics in each decennium. For Driver-studies more variation can be observed, namely that speeding, yielding and seatbelt use have been the most important research topics. Furthermore, in earlier decennia the research focus shifted more often, showing different top three topics between the 1970s and 1990s. However, since the 1990s the main research efforts have focused on the same three topics. Finally, only two studies during the 1980s were found that focused on yielding. There is no clear explanation why this topic received relatively little attention, while it was present in the top three research topics during the other decades.

Table 4 Evolution of the top three research topics per road user category from 1970, for topics that have been researched at least twice per decennium. Between brackets is the number of publications.

	1970-1979	1980-1989	1990-1999	2000-2009	> 2010
VRU	Crossing (2)	Crossing (2) Yielding (2)	Crossing (7) Yielding (2)	Crossing (23) Yielding (17) RLR (4)	Crossing (51) RLR (16) Yielding (13)
Driver	Yielding (7) Speeding (3) Overtaking (2)	Seatbelt (12) Speeding (11) Crossing (6)	Speeding (11) Crossing (8) Yielding (6)	Yielding (22) Speeding (20) Crossing (18)	Speeding (33) Yielding (28) Crossing (21)

3.4.2 Behavioural indicators

An overview of the 38 identified behavioural indicators is given in Table 5. They were categorized to gain insights into the complexity of the measurements by distinguishing between simple yes/no or other binary measurements and more detailed types of measurements (e.g. continuous and categorical data types). It was found that most indicators (23/38) have been examined using yes/no-measurements, including four indicators for which both types of data were collected. Yielding, for example, was found to be measured as a yes/no-variable in older studies, while more recent studies included more detailed measurements (e.g. hard, soft or no yield). The findings show that yes/no-measurements are most common: at least 78% of VRU- and 49% of Driver-studies included at least one of such observation. Speed has been measured most often for both study types, followed by red-light running for VRUs and headways for Drivers. Furthermore, the results show that the data collection process focuses on multiple aspects while examining the behaviour of interest. For example, only 16% of Driver-studies focused on speeding behaviour specifically, but almost 60% of all Driver-studies included speed measurements.

Table 5 The types of behavioural indicators, sorted on occurrence in VRU-studies. Between squared brackets the occurrence in percentage for VRU- and Driver-studies.

Yes/No [78% ; 49%][1]	**More detailed [65% ; 43%][1]**	**Both [53% ; 68%][1]**
Red-light running [38% ; 10%]	Crossing path [21% ; 2%]	Speed [40% ; 57%]
Jaywalking [19% ; 0%]	Waiting time [20% ; 4%]	Looking [24% ; 3%]
Gap acceptance [15% ; 10%]	Waiting position [15% ; 1%]	Yielding [13% ; 15%]
Evasive action [12% ; 3%]	Lateral position [11% ; 11%]	Merging [1% ; 4%]
Protective clothing [7% ; 0%]	Crossing time [9% ; 1%]	
Carrying items [7% ; 0%]	Gap size [7% ; 5%]	
Pedestrian Push Button Usage [6% ; 0%]	Headway [5% ; 18%]	
Mobile phone [5% ; 4%]	Yielding distance [3% ; 2%]	
Wrong-way driving [5% ; 0%]	Other distractions [3% ; 1%]	
Turn indicator [4% ; 3%]	Other violations [2% ; 1%]	
Lane change [3% ; 7%]	Lane choice [1% ; 1%]	
Stop-sign compliance [3% ; 2%]	Distance to Stop Line [0% ; 4%]	
Use of lights [3% ; 1%]	Merging distance [0% ; 2%]	
Stop/go decision [2% ; 8%]	Overtaking attempts [0% ; 1%]	
Yellow-light running [2% ; 4%]	Intersection Entry Time [0% ; 1%]	
Overtaking [2% ; 4%]		
Smoking [1% ; 1%]		
Seatbelt [0% ; 10%]		
Child restraint [0% ; 1%]		

[1] At least one indicator in this category has been measured

3.4.3 Single-vehicle crashes

Aarts, L.T. et al (2016) examined crash data in the period 2000-2014 of nine EU-member states and found that between 22-49% and 64-85% of all recorded crashes of car occupants and bicyclists respectively were single-vehicle crashes. Furthermore, the recording of single-vehicle crashes is subject to underreporting, especially with regard to cyclists where reporting levels are estimated to be around 10% (Elvik & Mysen, 1999).

This is important, since the previous paragraphs showed that most publications have focused on traffic events where interaction with other road users is required (either directly or indirectly). However, behaviours that are related to single-vehicle crashes and are not influenced by the presence of other road users have received less attention. A substantial portion of driver studies (16%) investigated speeding behaviour, but for vulnerable road users almost no studies investigating other aspects than interacting behaviours were observed. Possibly, research questions targeting this issue have used other methodologies that, until now, are more suitable (e.g. naturalistic driving and self-reported driving behaviour studies), since it is difficult to predict when and where a single-vehicle crash will occur.

3.4.4 Validity

Although a wide variety of indicators has been used to measure road user behaviour, efforts to validate them are very rare. The literature only shows a direct relation between speed and safety (Elvik, 2004). It seems that in general behavioural indicators are selected based on engineering judgement, since typically no justification or insights in the selection of the indicators is given. Behavioural observation studies focus on revealed behaviour under 'normal' traffic conditions, since it is not possible to predict where and when crashes will occur. It is possible that during data collection periods crashes are observed, however, they will not provide a sufficient sample size to base conclusions on. In order to make conclusions about safety, these studies most often compare revealed behaviour with guidelines (e.g. lateral overtaking distance), law violations (e.g. red-light running) or the extent to which behaviour changes after implementation of a safety improving measure (e.g. more yielding after installation of a yielding sign). Naturalistic driving studies may offer the opportunity to validate these behavioural indicators, if necessary, since this methodology enables the collection of detailed information of both actual crashes and 'normal' traffic conditions. Another opportunity to validate and study behavioural indicators in more detail is the use of the increasing number of cameras and other traffic data collection devices (radar and lidar) installed by governments and road agencies. However, acquiring the necessary permissions to use these data can be a challenge, given that these traffic data collection devices are mainly installed for monitoring purposes and that privacy legislations are becoming more strict.

3.5 Methodological aspects

3.5.1 Research set-up

One limitation of behavioural observation studies is that there is no possibility to manipulate traffic conditions, so researchers are dependent on what happens at the observation site. Several researchers have used different approaches to overcome this limitation. For example, Goddard et al (2015) used a semi-controlled research design, in which instructed pedestrians were used to force yielding events on a zebra-crossing. It enabled them to efficiently collect data on motorists’ yielding behaviour. Other studies made use of a moving observer to overcome the problem that one cannot predict at which location a certain traffic event will take place. For example, Walker (2007) instructed a cyclist to cycle a certain route and measured the lateral overtaking distance between motor vehicles and the instructed cyclist. The use of these methodologies shows a certain degree of flexibility in the methodological setup of road user behavioural observation studies, in order to overcome some limitations. However, as a trade-off, only the behaviour of the uninstructed road user could be analysed, since the behaviour of the instructed road-user will not provide any meaningful information.

3.5.2 Selection of locations

When performing an on-site behavioural observation study, two approaches can be used for selecting relevant locations: selecting locations where the number of reported crashes is relatively high, possibly due to location-specific aspects, or selecting locations that are as similar as possible and differ based on the characteristics of interest, to limit the influence of confounding factors. In our review we only encountered studies that used the latter approach. This is most likely explained by the fact that the observation of locations with high crash occurrence are too specific in such a way that estimating the transferability of the acquired results is difficult. Such studies are probably published as research reports in the grey literature. Furthermore, it should be mentioned that sampling bias and the limited number of locations that are typically observed in a behavioural observation study can also influence the transferability of results.

3.5.3 Control groups

Around one third of the VRU-studies and 42% of the driver-studies focused on the evaluation of a certain measure, for which three research designs have been used: before-after, with-without and cross-sectional observation. The first two designs compare the safety levels at one location with and without the treatment in place, while cross-sectional research designs compare locations with and locations without the treatment. For before-after studies the treatment has a permanent nature (e.g. installation of speed enforcement system), while for with-without study designs series of treatments could be tested (e.g. different designs of pedestrian warning signs at pedestrian crossings). When using these two designs, researchers should be careful of the trend effect: an increase or decrease in traffic safety levels can also be partly due to general trends of road user behaviour in general. To limit this bias, control groups can be used. However, our findings suggest that their use is not common practice in road user behaviour observation studies, since only 20 publications (12% of studies using before-after or with-without design) were found that used control groups. These publications reported that results needed to be adjusted, since the trend effect influenced the findings, and in the case of Islam et al. (2014), the effect was significant.

3.5.4 Reporting study characteristics

There is no standard format for researchers to describe study characteristics, which limits the transparency and transferability of research results. During the information extraction process, difficulties arose in determining the inclusion of heavy goods vehicles. Some authors explicitly stated their in- or exclusion, either by mentioning in-text or including them in result tables, while most studies limited themselves to mentioning motorized vehicles only which, based on descriptions, implied at least the inclusion of car drivers. It was therefore not possible to include heavy goods vehicles as a separate road user category in our review. Secondly, it was observed that information regarding the observation period is not always complete. Our analyses examined three characteristics (peak/off-peak, day/night and week/weekend) that are important aspects when comparing results of different studies, but in many cases one or more of these characteristics was not specified by the authors. Furthermore, almost 20% of the studies did not mention the sample size. To ensure transparency and transferability of research results a certain type of research protocol should be considered, in order to make sure that important aspects of the observation period are included in the description of the study methodology. Finally, the concept of 'interaction' should also be included in such protocol, stating which traffic situations were regarded as an event of interest.

4. Discussion and conclusions

4.1 Strengths and limitations of this study

In total, 600 journal articles were included in this scoping review. We could access all but 23 relevant publications, from which information was extracted in order to examine the range and extent of behavioural observation studies. The search limited itself to peer-reviewed journal articles published in English, restrictions applied in other scoping reviews as well (Pham, 2014), in order to include some form of quality assessment, which is typically not part of a scoping review (Levac, Colquhoun and O'Brien, 2010). However, examining publications in the grey literature can provide additional insights into the current practices of road user behavioural observation studies in general (Hagenzieker et al., 2014). Furthermore, it is possible that the state-of-the-art presented in this review differs from the current practices that might have been reported in the grey literature more often. This can be an interesting topic for further research.

We cannot guarantee that our scoping study is without bias, but efforts were made to avoid bias. Multiple major databases known to contain peer-reviewed journals were selected and two reviewers were used in the entire process of data extraction of eligible articles. However, it should be noted that the categorization and interpretation of the data can be subject to reviewer bias: other researchers for example might approach the categorization of the topics and indicators differently. Finally, this study only examined the literature at a high level, where certain types of data were aggregated in order to provide a detailed yet concise overview of the findings. For example, the measurement of speed included the intrinsic value (e.g. speed), derivatives of this indicator (e.g. acceleration rates) and simplified binary measurements (e.g. slowing down and overspeeding).

4.2 Trends and developments

This review focused on a high-level description of the findings of the descriptive analysis. As a result, an overview of the most common practices is provided, indicating the areas of road safety research that have been targeted most by behavioural observation studies. This review provides a structured overview and discussion of the main trends that can be observed for behavioural observation studies published in the scientific literature, which can help other researchers to identify relevant topics for further research considering the knowledge that has already been reported in the vast amount of studies published up to and including 2015. Directing future research by highlighting important topics is difficult, since there is no universal list of the most important road safety problems. Furthermore, the topics on such list will most likely be dependent on driving cultures. Nevertheless, researchers with a particular interest for a certain safety problem can, based on this review, identify the research efforts already reported in the scientific literature and approaches used to study it. It should be noted, however, that this study only provides information on traffic safety research based on behavioural observation, while areas that have received little attention may be researched more often using other safety evaluation methods. For example, motorcyclists' behaviour is commonly investigated using driving behaviour questionnaires (e.g. Ozkan et al., 2006, Elliott et al., 2007), which focus on the attitudes and beliefs of individuals to perform certain behaviours, rather than direct behaviour observations. This highlights that behavioural observation studies are useful to study revealed behaviour, but that it is not possible to use them when one is interested in the underlying motivations, beliefs and attitudes.

A wide variety of behavioural indicators was found and showed an important challenge of using direct human observations. Over time, many binary measurements have been replaced with continuous variables, providing more depth in the data analysis process. Validation efforts to examine the link between these indicators and traffic safety levels are rarely found. Determining indicators of interest seem the result of engineering judgement, where the comparison with safety is based on how behaviour relates to design guidelines or traffic rules or to what extent behaviour changes between different conditions.

The review found adaptations of on-site behavioural observation techniques that enable a more efficient data collection process by forcing events of interest, in which the road user under investigation remains unaware of its participation into a research project (beforehand). Examples include instructed road users and moving observers. The review found that control groups are important to control for trend effects when before-after and with-without research designs are used. Regarding reporting research findings, a more uniform way of reporting characteristics of the observation period is needed for more transparency, comparability between studies and possible transferability of the results. Finally, this review focused on a high-level description of the scientific literature available on behavioural observation research. It was not within the scope of this review to focus on individual studies that possibly highlight important aspects, either methodologically or application-wise, for future research efforts. Further research focusing on these types of studies might formulate concrete recommendations for conducting behavioural observation studies in general.

Several important trends were highlighted that can influence future research efforts. The ongoing developments of automated video analysis software tools can be the next methodological step forward in video-based behavioural observation studies. Once fully functional, they will be able to objectively measure behaviour, without human input during the data collection and analysis processes. Other spatial sensors of interest are lidars, which are receiving increased attention in safety research (e.g. Simons-Morton et al. (2005) and Tarko et al (2016)) and enable more detailed measurements. Combined with the increasing number of cameras installed in the road network, it can also enable more research into behaviours that influence single-vehicle crashes, a topic that has not yet received much attention.

4.3 Road user behavioural observation studies

Road user behavioural observation studies have been published in scientific literature for over 80 years and are being conducted on a large scale today. It was found that the number of publications increased rapidly after 2000, which indicates that behavioural observation research is important to study road user behaviour and examine traffic safety problems at locations or for target road user groups of interest. Their use is diverse, including monitoring, evaluating the safety effects of a specific measure and developing microsimulation models.

Behavioural observation is particularly useful to monitor the frequency of behaviour and to evaluate the effects of road safety treatments and strategies. They have as main strength that they use direct observation of road user behaviour in a natural setting, with limited behavioural adaptation effects. Therefore, such studies gain more knowledge and insights in road user behaviour and enables to identify and describe some of its features. As with all road safety research methodologies, limitations exist. For example, generalizability of results can be an issue, since road user behaviour is observed at a specific location with its own unique location specific characteristics. Furthermore, since one does not know when and where crashes will occur, behavioural observation is less favourable when one is interested in quantifying road safety as expected number of crashes. In order to provide a comprehensive overview of traffic safety levels at a certain location, the combination with other road safety methodologies (e.g. crash data analyses, driving simulator research or self-reporting tools) remains necessary.

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Appendix A

Table A.1 General characteristics of the included studies split out into the four main road user types.

Study Type	**VRU (n=193)**						**Driver (n=485)**	
Road User Type [1]	Pedestrian		Cyclist		Motorcyclist		Car driver	
	(193 = 100%)		*(193 = 100%)*		*(193 = 100%)*		*(485 = 100%)*	
	#	*%*	#	*%*	#	*%*	#	*%*
Amount of studies	136	*70*	54	*28*	28	*14*	484	*100*
	(136 = 100%)		*(54 = 100%)*		*(28 = 100%)*		*(484 = 100%)*	
	#	*%*	#	*%*	#	*%*	#	*%*
Publication years[2]								
1930 – 1939	-	-	-	-	-	-	1	*0*
1940 – 1949	-	-	-	-	-	-	1	*0*
1950 – 1959	-	-	-	-	-	-	4	*1*
1960 – 1969	-	-	-	-	-	-	4	*1*
1970 – 1979	4	*3*	2	*4*	-	-	19	*4*
1980 – 1989	6	*4*	-	-	-	-	56	*12*
1990 – 1999	10	*7*	6	*11*	1	*4*	56	*12*
2000 – 2009	47	*35*	7	*13*	6	*21*	134	*28*
2010 – 2015	69	*51*	39	*72*	21	*75*	209	*43*
Geographic location[1,3]								
The Americas	60	*44*	18	*33*	1	*4*	260	*54*
Europe	34	*25*	18	*33*	6	*21*	108	*23*
Africa	-	-	-	-	1	*4*	2	*0*
Eastern Mediterranean	13	*10*	-	-	1	*4*	30	*6*
South-East Asia	6	*4*	2	*4*	6	*21*	9	*2*
Western Pacific	27	*20*	17	*32*	13	*46*	76	*16*
Data collection tool[1]								
Human observer	62	*46*	12	*22*	8	*29*	158	*33*
Static camera	76	*56*	43	*80*	19	*68*	241	*50*
Moving camera	-	-	-	-	-	-	25	*5*

Loop detectors/pneumatic tubes	-	-	2	*4*	3	*11*	68	*14*
Speed gun	-	-	4	*7*	5	*18*	69	*14*
Sensor	-	-	1	*2*	1	*4*	21	*4*
Other	-	-	-	-	-	-	11	*2*
Main research Purpose								
Monitoring	73	*54*	31	*57*	16	*57*	228	*47*
Evaluation	46	*34*	20	*37*	6	*21*	206	*43*
Model development	14	*10*	2	*4*	6	*21*	48	*10*
Software development	3	*2*	1	*2*	-	-	2	*0*
Research Design								
Single observation	86	*63*	32	*59*	22	*79*	275	*57*
Before-after observation	30	*22*	11	*20*	1	*4*	105	*22*
With-without observation	9	*7*	5	*9*	2	*7*	56	*12*
Cross-sectional observation	11	*8*	6	*11*	3	*11*	48	*10*

[1] multiple categories per study possible, [2] studies up to and including 2015 are included, [3] according to the WHO definitions (2017)