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The potential of naturalistic driving for in-depth understanding of driver behavior: UDRIVE results and beyond

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ABSTRACT

Within the UDRIVE project, a rich cross-European naturalistic driving database was created which includes everyday driving data on car and truck drivers and powered two-wheeler riders. The database provides extensive, reliable insights into driving behavior in real traffic as a foundation for improving the safety and sustainability of European road traffic. This paper discusses the characteristics of the data in the UDRIVE database—elucidating key methodological choices and presenting a selection of results to date.

A priority of the study design was obtaining in-depth information on driving behavior, permitting the exploration of diverse research questions. A tailor-made data acquisition system collected very comprehensive data. A total of 287 drivers/riders participated. The sample size restricts the addressable research topics to common behaviors in everyday driving and limits the generalizability of results. However, the data are extensive and promising analyses have already been performed. The results show differences between European countries for distracting activities, seatbelt use, and looking behavior towards cyclists at urban intersections. Moreover, it shows that European drivers engage less in mobile phone use than U.S. drivers. It is likely that European drivers differ in other ways, also—highlighting the dataset's value for developing and implementing targeted safety measures, for the E.U. and its individual countries.

Based on the comparison of the different studies, the paper introduces the general conceptual framework for naturalistic driving studies, providing insight in the relation between the scope of a naturalistic driving study and the key methodological choices on sample selection and data acquisition system.

1. Introduction

In the European Union, around 25,000 people die and around 1,500,000 become injured on roads (Adminaite et al., 2018) each year. Road transport is also one of the main sources of air pollution, which remains the number one environmental cause of death in the European Union, leading to about 400,000 premature deaths each year (EEA, 2018). There is a strong need for successful policies and technological innovations to reduce those numbers and move towards a safer and more sustainable Europe.

To develop effective evidence-based policy measures and technological innovations, there is a need for better insight into road-user behavior. Traditional research methods such as driving simulator studies, test-track experiments, and even controlled on-road experiments are unable to capture everyday choices in driving and riding (Carsten et al., 2013), such as when and to what extent drivers engage in distracting activities, and in which conditions. Similarly, these methods typically do not capture the full range of vehicle dynamics and driving situations during everyday life, and hence are ill-suited for accurately assessing eco-driving performance. It is also very difficult (if not impossible) to use controlled experiments to study crash causation. Such situations can in part be studied through self-reports/questionnaires, but for in-depth analysis they require time-series data from everyday driving in real traffic (Bärgman, 2016).

Naturalistic driving studies can be used to capture such data, and overcome the limitations posed by traditional methods; their results can provide new scientific insights, help develop tailored and targeted policy measures, and support industry in the development of new measures to improve the safety and sustainability of our road transport system. A naturalistic driving study can be defined as "A study undertaken to provide insight into driver behaviour during everyday trips by recording details of the driver, the vehicle and the surroundings through unobtrusive data gathering equipment and without experimental control" (Van Schagen et al., 2011). It is a relatively new

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research method that “looks over the driver’s shoulder” and provides in-depth insight into road-user and vehicle behavior. Naturalistic driving allows researchers to observe and analyse interrelationships between the driver, the vehicle, the road, and other traffic in a variety of situations, from normal driving to conflict situations and even actual crashes. This type of information is useful for reducing road transport casualties, the environmental burden of road transport, and congestion (van Schagen and Sagberg, 2012). Naturalistic driving data have also been used by the automotive industry to create models of driver behavior in critical situations, and understand the mechanisms behind crashes caused by, for example, inattention (e.g., Engström et al., 2013; Markkula et al., 2016; Schneidereit et al., 2017; Victor et al., 2015).

1.1. Previous and ongoing naturalistic driving studies

The naturalistic research method was first applied to driving on a significant scale in the 100-Car Naturalistic Driving Study by VTTI in the U.S. (Neale et al., 2005). The study showed the potential of the nascent methodology, raising interest across the globe. Since this study, a very large-scale naturalistic driving study has been completed in the U.S. through the Strategic Highway Research Program 2 (SHRP2). In SHRP2 approximately 2000 cars were equipped with tailor-made data acquisition systems (DAS), resulting in a sample of over 3000 car drivers driving for one year, totaling almost 80 million kilometers in six different areas (Blatt et al., 2015).

The Canadian and Australian naturalistic driving studies can be considered as extensions of SHPR2. They used the same DAS, but had significantly lower sample sizes. The Australian sample consists of 352 drivers (age 21–70 years) from New South Wales and Victoria driving their own private vehicle for four months, resulting in approximately 1.8 million kilometers of driving data (Grzebieta et al., 2017). The Canadian study has now been finished and analysis projects are ongoing. One hundred and forty cars where instrumented and driving primarily in Saskatoon, Saskatchewan, and the surrounding area for 12 to 24 months (VTTI, 2017). Approximately 1.8 million kilometers were driven (cars, pickup trucks and minivans) by 149 drivers (https://insight.canada-nds.net/).

In Europe there have been several smaller-scale naturalistic driving studies. The European project INTERACTION, completed in 2012, collected and analyzed data from 100 vehicles that drove for about four months each. Driver behavior was logged by four cameras, a Global Positioning System sensor, and a number of additional sensors. The data were used to investigate the use of in-vehicle equipment while driving (Christoph and van Nes, 2015; Christoph et al., 2013; Haupt et al., 2015; van Nes et al., 2012). The EuroFOT project, also completed in 2012, was a naturalistic field operational test (NFOT) in which vehicles were instrumented with the goal of evaluating the safety benefit of a range of active safety systems ((Bärgman, 2016; Benmimoun et al., 2011; Ljung-Aust et al., 2011). The resulting data have also been used for behavior research (e.g., Tivesten and Dozza, 2014; Morando, Victor and Dozza, 2016) and for developing methods for analyzing naturalistic driving data (Dozza, Bärgman and Lee, 2013). Other naturalistic driving studies in Europe include the predecessor of UDRIVE, ‘Prologue’ (Sagberg et al., 2011; van Schagen et al., 2010), and SeMiFOT (Victor et al., 2010). Prologue also investigated the value of site-based analyses complementing naturalistic driving observations (van Nes et al., 2013).

1.2. UDRIVE, the first large-scale European naturalistic driving study

UDRIVE was the first large-scale European naturalistic driving study. It resulted in a large amount of behavioral data from across Europe on three different transport modes: car driving, truck driving, and powered two-wheeler (PTW) riding. The UDRIVE study, co-funded by the European Commission, was realized by a collaboration of 19 partners from research institutes, academia, and the automotive industry. The total project budget was just over 10 million Euros. It lasted for almost five years, from October 2012 to June 2017. The objective of UDRIVE was to generate a rich, cross-European naturalistic driving dataset for cars, trucks, and PTWs in order to perform analyses for gaining in-depth insight into everyday driving behavior in real traffic, in order to identify ways for improving road safety and sustainability. Preliminary analyses were performed during the UDRIVE project itself.

The first objective of this paper is to show that naturalistic driving data, specifically UDRIVE data, provide many opportunities for research in road safety and sustainability, albeit with some limitations. The data’s potential will be demonstrated by presenting and discussing the methodology and some examples of results of the UDRIVE study. The naturalistic driving method is typically much more costly and time-consuming than traditional observation, surveys, or experimental studies. Hence, it is important to make well-informed decisions about when and how to conduct naturalistic driving studies.

This paper’s second objective addresses the need to plan carefully before undertaking a naturalistic study, presenting a conceptual framework for defining the scope of naturalistic driving studies based on the key methodological choices on sample configuration and data collection. The framework is based on comparing the key features of the UDRIVE study design and those of large-scale naturalistic driving studies in other parts of the world, is useful for selecting the best fitting existing dataset to use for studying a new research question and for decision-making on size and scope of future naturalistic driving studies.

2. Methodology

2.1. Design of UDRIVE data collection

The UDRIVE study was designed to facilitate analyses that use a variety of methods and address a wide range of research questions. It was decided to log data continuously; driving is a continuous task, so understanding it correctly requires the analysis of continuous data. Event-triggered data collection would not be sufficient, since factors that contribute to safe and efficient driving behavior are not concentrated around events. It was also a priority to collect very detailed data, to gain in-depth insight into driving behavior. The specific requirements for the data acquisition system (DAS) were set by establishing the research questions to be asked (Barnard et al., 2016). As no existing system fulfilled these needs, a tailor-made DAS was developed. Most important reasons were the need for comprehensive video information and automatic detection other road users including cyclists and pedestrians. Moreover, the relevance of the UDRIVE study goes beyond car interactions with other road users was extended by including trucks and powered two-wheelers (PTWs), which have their own driving characteristics and safety challenges. These vehicles used the same custom DAS as the cars.

2.2. Participants

To enable comparisons between car drivers in different countries across Europe, car data collection took place in five different European countries: France, Germany, the Netherlands, Poland, and the United Kingdom (see Fig. 1). These countries were selected to have a diverse perspective of European riding, including countries from the South, East and North West of Europa and including countries with different road safety performance.

In each country, apart from the Netherlands, data was collected for a period of 12 to 18 months for each driver, whose private vehicle was equipped with the UDRIVE DAS. In the Netherlands, ten vehicles were leased and equipped with the DAS, and data were collected in three successive six-month-long periods of ten participants each. Data collection for PTWs, which were leased, took place in Spain and lasted for 12 to 18 months per rider. Data collection for trucks took place in the Netherlands and lasted for 18 to 24 months per driver.

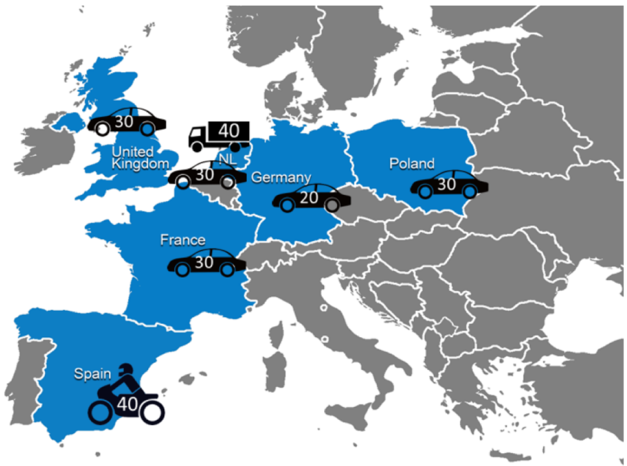

Fig. 1. Overview of countries were data was collected per vehicle type (cars, trucks and PTW's).

2.2.1. Recruitment criteria and method

For the car and PTW drivers, recruitment criteria for mileage, age, and gender were used. Car drivers needed to drive at least 10,000 km per annum and PTW drivers at least 5000 km per annum. An equal distribution between two age groups, 18–25 and 30–65 years old, was aimed for. A minimum quota of 40% per gender was targeted for the car drivers; for the PTW drivers the quota was set to 30%. Additionally, attempts were made to recruit multiple drivers per car (e.g., when the car was used by more than one driver in the same household). The DAS was developed for specific makes and models (Renault Clio III, Clio IV, and Megane for passenger cars; Volvo FL and FM for trucks; and the Piaggio Liberty 125 for PTWs); thus only drivers with one of these models could participate. For the truck drivers, no recruitment criteria were set up as it was anticipated that merely finding enough volunteers would be a challenge.

The participants were recruited through a variety of channels: internet, social media, advertisements in local newspapers, partners' internal networks, and flyers distributed at car dealerships or in carparks (Castermans et al., 2017a). Local FIA automobile clubs circulated the call for participation to their members. Truck drivers were recruited by contacting fleet owners. If the fleet owner agreed to participate in the study, individual drivers were approached. Both fleet owners and drivers were assured that data collected would never be shared with the fleet owner. For the PTW's, approximately half of the participants were recruited from employees of the company managing the PTW fleet. For all participants, participation was voluntary.

2.2.2. Participant sample

The final participant sample consisted of 192 car drivers, 48 truck drivers, and 47 PTW riders distributed across four age categories: 18–29, 30–39, 40–49, and 50–65 years; see Table 1 for details (Castermans, 2017b). In general, the criterion of equal distribution between the two age groups (18–25 and 30–65 years old) was not met. The targeted gender distribution of at least 40% male and 40% female was achieved for France, Netherlands and UK. In Poland and Germany, the gender distribution was unbalanced, respectively 29% and 37% female. Almost all the truck drivers were male (98%) and for the PTW drivers, males were also overrepresented (74%).

2.2.3. Participant briefing and informed consent

All participants were initially briefed about the project and their intended participation, using standard protocols and briefing materials. Participants received an informed consent form describing the study and explaining their rights and duties in their local language. If the participants were willing to participate, they signed the informed consent, as did a representative of the project. Participants filled in questionnaires, and had full-face and profile pictures taken for electronic driver identification while the vehicle was being instrumented. A generic debriefing was held at the end of their participation.

Table 1
Distribution of participant age and gender across the UDRIVE countries.

Vehicle Type & Country	Participants (Vehicles)*	Gender		Age			
		Male	Female	18–29	30–39	40–49	50–65
Cars	**192 (120)**	**55%**	**45%**	**11%**	**31%**	**25%**	**33%**
France	45 (30)	47%	53%	9%	27%	31%	33%
Germany	30 (20)	63%	37%	17%	24%	7%	52%**
Netherlands	33 (10)	55%	45%	9%	30%	27%	33%
Poland	31 (30)	71%	29%	6%	48%	39%	6%
UK	53 (30)	49%	51%	15%	28%	19%	38%
Trucks	**48 (32)**	**98%**	**2%**	**6%**	**13%**	**32%**	**49%**
PTWs	**47 (40)**	**74%**	**26%**	**9%**	**55%**	**34%**	**2%**
TOTAL	**287 (192)**	**66%**	**34%**	**10%**	**32%**	**27%**	**31%**

* There are more participants than vehicles because of secondary drivers.
** In Germany, the age category 50–65 includes one 81 year-old participant.

2.2.4. Participant incentives

The incentive for car and truck participants was 800 Euros, divided into three payments: after six months, after 12 months, and after de-installation of the DAS. Participants using leased vehicles (the Dutch car drivers and the Spanish PTW riders) received free use of the leased vehicle (excluding fuel costs) as an incentive, instead of the 800 Euros.

2.3. Materials

2.3.1. Data acquisition system (DAS)

Early in the project it was realized that there was no off-the-shelf DAS that was able to provide the information needed to answer the UDRIVE research questions. Therefore, a tailor-made system was developed, which included: DAS-specific sensors (e.g., accelerometers and angular rate sensors), GPS, the ability to record multiple Controller Area Network (CAN) busses, a smart camera to detect other road users and obstacles (Mobileye), and up to eight cameras with resolutions up to 464x363 pixels (Augros et al., 2013; see Fig. 2). The DAS was further adapted to fit the individual makes and models of vehicles in the UDRIVE study. The instrumentation of the vehicles took on average four hours per vehicle, the first vehicles took more time to familiarize oneself with the installation process. The DAS implementation for cars and trucks was approved (homologated) by the respectively Renault and Volvo to ensure that the system did not interfere with the normal functioning of the vehicle. The installation, calibration, and configuration of the UDRIVE DAS took an average of four to eight hours per vehicle.

A total of 270 measures (signals) were collected by the DAS for cars and trucks. For PTWs the number of measures was lower (approximately 30) because CAN data and smart camera data (MobilEye) were unavailable. The collected measures were enriched with approximately 50 map attributes (geographic information system; GIS). During the analysis phase of the project more than 400 additional measures were derived.

2.3.2. Data processing and final dataset

The data collected from the vehicles were encrypted and stored on hard drives. The hard drives were periodically replaced and sent to one of three Local Data Centres for data pre-processing. Local Data Centres shipped the pre-processed data to the Central Data Centre. Data collection, transfer, and pre-processing were continuously monitored by the On-line Monitoring Tool, which provided a complete overview of the data collected: their physical location (in the vehicle, at a Local Data Centre, in transit, or at the Central Data Centre) and their location in

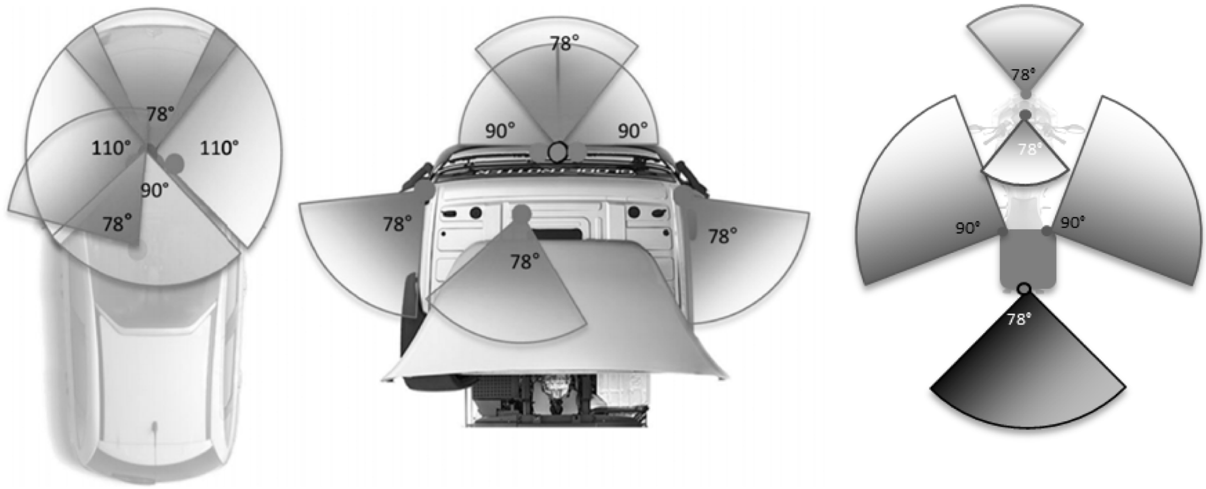

Fig. 2. The camera views for cars (left), trucks (center), and PTWs (right). * For cars the foot camera and passenger camera are not shown; for trucks the foot camera is not shown.

the data-processing chain. The Central Data Centre performed final data processing, data cleaning, and driver identification as well as offering remote access to the analysts working with the data.

A total of around 4 million kilometers (87,870 h) of driving data were collected. After data processing, data cleaning and driver identification the final analyzable dataset consisted of 2,3 million kilometers (53,157 h), approximately 60% of the collected data. For cars 7% of the driven data were excluded, exclusions were mainly due to drivers not being (identified as) consented drivers. For trucks 65% of the data were excluded, of these, 22% were excluded due to drivers not being consented drivers and 43% were excluded due to no available face video and thus not being able to do the consented-driver verification – often due to sabotage/damage to cameras in the cabin.

Fig. 3 presents the amount of analyzable data in terms of number of trips, distance driven and hours driven across the three vehicles types and (for cars) across the five countries. The gender balance in terms of driving time in the final data was similar to that of the original data (see Table 1): for car drivers across all countries driving time of male and female was almost equal; for PTWs and trucks, males generated respectively 69% and 98% of the driving hours.

Data were analyzed by a variety of statistical software programs after being processed in a custom-made data processing tool (SALSA) based on Matlab (Bärgman et al., 2017).

2.3.3. Questionnaires

The following validated questionnaires were filled in by the participants: driver attitude questionnaire (Parker et al., 1996; speeding and close-following items only), driver behavior questionnaire (Lajunen et al., 2004; error and violation items only), driving style questionnaire (French et al., 1993; all items), locus of control (Özkan and Lajunen,

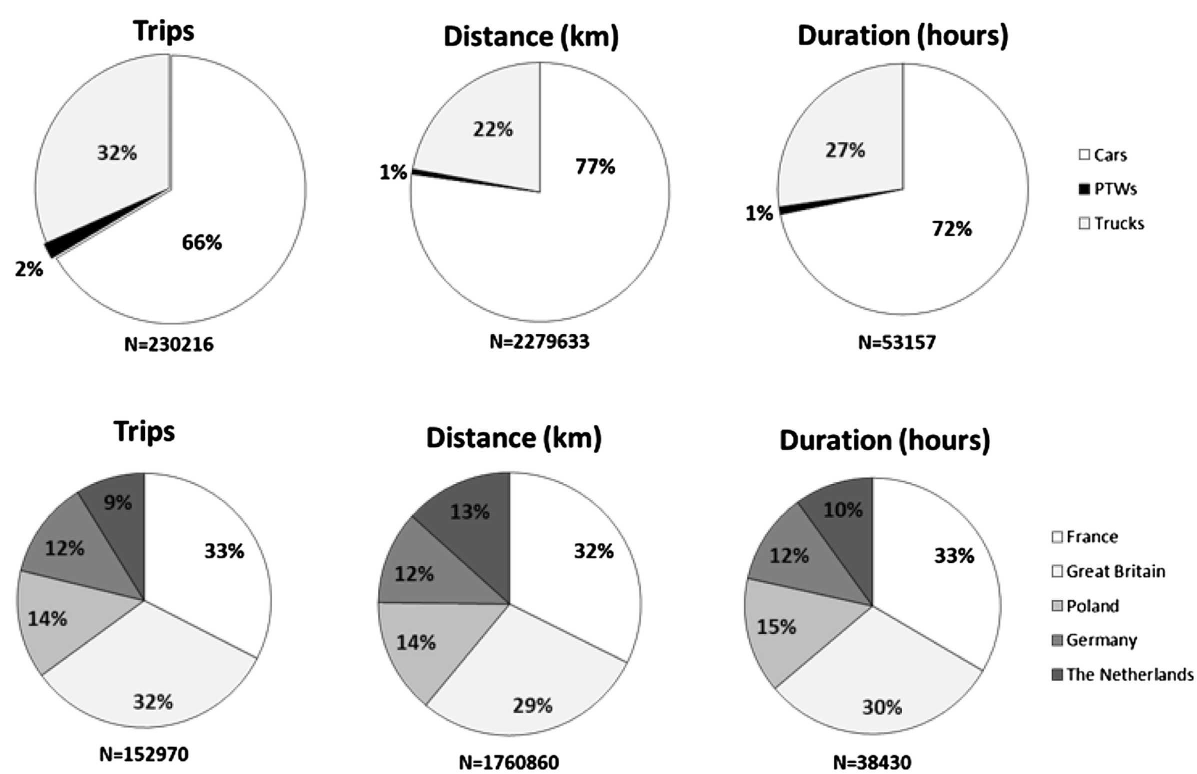

Fig. 3. The analyzable UDRIVE data for the three types of vehicles (top) and, for cars, per country (bottom).

2005; all items), and sensation seeking (Arnett, 1994; all items). Accident and traffic violation histories were also recorded.

2.3.4. Privacy and data protection

Several privacy-related aspects were considered during the setup of the study. The UDRIVE project developed a Data Protection Concept (DPC), which specifies the constraints and requirements for data handling throughout the project. The DPC describes the different locations that handle the data (e.g., Local Data Centre, Central Data Centre, and Analysis Site), as well as the locations' interactions, from the moment the data are collected until the end of their lifetime.

3. Results

During the UDRIVE project several analyses covering the following research areas were performed: distraction and inattention (Carsten et al., 2017), eco-driving behavior (Heijne et al., 2017a), interaction with VRUs (Jansen et al., 2017), and risky driving (Dotzauer et al., 2017). The section below presents a selection of their results to illustrate the potential of the UDRIVE data. Based on these results, opportunities to enhance safety on European roads have already been identified (Tattegrain et al., 2017).

3.1. Distraction and inattention

Distraction and inattention are common crash causation factors (Dingus et al., 2016). Based on the UDRIVE data, Carsten et al.'s 2017 results indicate that car drivers were involved in distracting activities for approximately 10% of their driving time. The most common distracting activity was hand-held mobile phone use, occurring on average approximately 4% of the driving time. In Poland, mobile phone use was significantly higher than in the United Kingdom, France, or Germany; Polish car drivers engaged in phone use during about 10% of their driving time, compared to 0–4% in the other countries. As reported by Christoph et al. (submitted), Dutch drivers spent over 9% of their driving time engaging in mobile phone-related tasks. This study also found that a number of driving-context factors were related to the frequency of mobile phone use, such as road type, driving maneuver, speed, and passenger presence.

The analysis of the UDRIVE data (Carsten et al., 2017) also showed that for truck drivers the overall involvement in secondary tasks was much higher than for car drivers—approximately 20% of the driving time. Truck drivers spent most of this time eating/drinking and using the phone (5% each). Further, almost half of the time using the phone comprised texting, reading, or other visual interactions.

3.2. Eco-driving behavior

There are many elements influencing eco-driving, such as velocity, braking, and gear shifting, and many underlying parameters, such as country, driver, road type, speed limit, and infrastructure. A comparison of UDRIVE eco-driving scores for country, driver age, and driver gender showed little to no correlation—at least none that is unambiguously independent of vehicle model, infrastructure, vehicle type, and other variables. However, the lack of correlation may be due to the limited amount of data, particularly notable when parameters are combined (Heijne et al., 2017b).

Nonetheless, some significant findings have been made. Heijne et al. (2017a) report that in general, braking is the greatest source of energy loss for most drivers at low velocities. The lost braking energy between the best and worst drivers varied from approximately 60% above to 60% below the average; some drivers lost four times more energy in braking than others. This difference can result in an increase in overall energy consumption of up to 10% in urban areas at low velocities. Investigating another aspect of energy loss due to braking, they also found that, during car-following, drivers with longer time-headway tend to lose less energy braking than those with shorter time-headway. In addition, idling losses are not insignificant, with an average idling time in urban driving of 15%, ranging from 0 to 50% across drivers and trips (Heijne et al., 2017a; Heijne et al., 2018).

3.3. Interactions with cyclists

The UDRIVE data revealed that car and truck drivers often did not check the blind spot for cyclists when making a right turn (left turn in the UK) at an intersection or roundabout (Jansen et al., 2017). Dutch car drivers performed shoulder checks (explicitly checking the blind spot) more often than drivers in France, Poland, or the UK. On average, truck drivers used their Class V mirror to check the blind spot in less than half of the maneuvers (Jansen et al., 2017).

In general, 70% of the instances of car drivers overtaking bicyclists were 'flying overtakings'—that is, the drivers did not change speed significantly before or during the overtaking (Kovaceva et al., 2018). In Poland, however, significantly fewer overtakings were flying (approximately 50%). In most European countries the lateral distance that drivers must legally maintain between their vehicle and the bicycle they overtake is 1.5 m. It is noteworthy that the UDRIVE data showed an average lateral distance of 1.65 m (SD = 0.64 m), indicating that around 40% of the bicycle overtakings occurred with a lateral distance below the legal threshold. Several factors affected the lateral distance during the overtaking, such as the speeds of the car and the bicycle, the width of the lane, and whether there was an oncoming vehicle.

A qualitative analysis was performed of 11 identified safety–critical events (SCEs) of vehicle-bicycle interactions, three between cars and bicycles and eight between trucks and bicycles, all on urban roads with a speed limit of 50 km/h or less. The analyses showed that the SCEs were caused by a combination of factors, including the presence of other traffic, infrastructure features (e.g., the width or curvature of the lane/road), unexpected cyclist behavior (e.g., slowing down), and driver maneuvers (e.g., overtaking). In none of the 11 SCEs was the car driver engaged in secondary tasks or exceeding the speed limit; in all cases, the drivers made relevant judgments and performed appropriately to avoid crashes (Jansen et al., 2017).

3.4. Interactions with pedestrians

Car-pedestrian interactions were investigated by analyzing 400 pedestrian-collision warnings in the UDRIVE data from the UK and France through cluster analysis (Jansen et al., 2017). The three most important conditions for conflicts between cars and pedestrians were the absence of facilities for vulnerable road users (VRUs), such as pedestrian crossings or sidewalks; high vehicle speed; and the sudden, unexpected appearance of pedestrians. Keeping the drivers aware and alert is key to reducing these conflicts.

3.5. Interactions with PTWs

With respect to interactions with PTWs, Jansen et al.'s 2017 analyses of UDRIVE data showed that, contrary to their initial hypothesis, drivers of cars do not keep shorter time-headways to PTWs than to cars and trucks.

An interesting result by Jansen et al. (2017) is on riding behaviour: across riders significant differences were found in speed choice and acceleration during manoeuvres and when making full stops prior to the manoeuvres. Riders appear to use a constant deceleration in the five seconds prior a full stop, but the magnitude of this deceleration varies between riders. These findings suggest that riders have different preferences (i.e., riding styles) regarding speed choice and acceleration.

3.6. Risky driving

Dotzauer et al. (2017) studied risky driving generally and reported some interesting results. The UDRIVE dataset contains seven identified crashes, all of them were categorized as damage only or light injuries, no serious injuries of fatalities. They showed that in approximately 87% of the car trips, drivers had their seatbelts fastened from start to end. This percentage differed from one country to another, with the lowest in Poland (76%) and the highest in the Netherlands (96%). In fact, country was the most important explanatory variable regarding seatbelt use, while gender and time of day were also significant. Men had a significantly higher unfastened seatbelt rate than women, and seatbelts were more frequently left unfastened for all or part of the trip during night-time driving than daytime driving, albeit for trips less than 325 m only.

Dotzauer et al. also found that drivers were relatively good at adapting to the environment and traffic situation when overtaking other cars or trucks. Drivers were less inclined to overtake in adverse weather conditions or when there was traffic in the oncoming lane. Notably, in approximately 12% of the overtaking maneuvers, the drivers violated legal restrictions (Dotzauer et al., 2017).

4. Discussion

The UDRIVE study was designed to create a cross-European dataset with detailed information on everyday driving behavior. This dataset aimed to provide better understanding of drivers' and PTW riders' behavior in relation to the driving context. Specifically, to provide better understanding of relevant safety and sustainability topics such as distraction and inattention, interaction with VRUs (cyclists and pedestrians), risky driving, and eco-driving. This section discusses the value and limitations of the UDRIVE naturalistic driving dataset in light of the objectives and the key methodological choices and in relation to other large scale naturalistic driving studies performed.

4.1. European naturalistic driving database

As mentioned, prior and parallel to UDRIVE, large-scale naturalistic driving studies had been conducted in the U.S., Australia, and Canada. Given that naturalistic driving studies are costly, the question is whether a separate European dataset has added value. Clearly, the more fundamental determinants of human behavior in traffic are universal, making the location of data collection irrelevant. However, driving behavior is also determined by cultural aspects, available infrastructure, legislation, traffic composition, and many other factors which do vary with geographic location and/or country.

A comparison of some of the UDRIVE results with those of the U.S. SHRP2 study reveals interesting differences. For example, while European drivers used their hand-held mobile phones for, on average, around 4% of the time spent driving (Carsten et al., 2017), for U.S. drivers the figure was 6% (Dingus et al., 2016). This difference confirms that European drivers do not necessarily exhibit the same driving behavior as non-European drivers; thus, in order to understand European driving behavior, it is necessary to have a European dataset.

4.2. Cross-country comparisons

The UDRIVE project collected data in different European countries, because drivers in different countries and cultures can be expected to have different driving behaviors. The results presented in this paper show behavioral differences between countries with respect to phone use, and seatbelt use and blind spot checking. This indicates that a diversified and targeted deployment of safety measures across Europe is required, rather than a 'one size fits all' approach. Even though UDRIVE's data for each country may not be representative of the overall population, the results of the UDRIVE analysis confirmed the cross-country differences in road user behavior.

For optimal cross-country comparisons, a strength of the UDRIVE data is that it is conducted with the same DASs and the same vehicle makes and models during the same time period, with similar criteria for participant sampling in each country. This design reduced potential instrument biases, increasing the validity of result comparisons.

Overall, the results from UDRIVE clearly confirm the importance of conducting studies across Europe. Insight into drivers' behavioral differences across countries could help explain differences in road fatality statistics and inspire and motivate national and European policy-makers to develop well-informed road transport policies and more effective safety measures individualized for each country.

4.3. The data acquisition system

Data collection took place with a DAS that was specifically designed and developed at the start of the UDRIVE project to answer a set of identified research questions. The UDRIVE DAS collected continuous, detailed data about the driver, the vehicle, and the context. Importantly, the DAS was also able to record interactions with both cyclists and pedestrians. The DASs of the three non-European large-scale naturalistic driving studies are very similar to each other, but different from the European UDRIVE study. Both the UDRIVE DAS and the SHRP2 DAS are tailor-made. While they both collect detailed time-series data on a large variety of variables, there are a few significant differences that have a clear impact on the scope of the studies.

The SHRP2 DAS made use of a radar, which can detect obstacles at a greater distance from the subject vehicle than the smart camera used in UDRIVE, and can extract relative speed to objects directly (Doppler). On the other hand, the smart camera in UDRIVE detects and tracks VRUs automatically. For the Australian study, an identical smart camera was added; however, that studies only recorded data related to near-collision warnings, whereas UDRIVE had access to continuously recorded data about all surrounding objects, identifying them (car, truck, PTW, bike, or pedestrian) as well as recording their distance, speed, and direction.

The SHRP2 DAS had four continuous camera feeds: forward, driver/left side, rear/right side, and cabin; a fifth camera took snapshots to capture passenger presence. The cars in the UDRIVE study had seven continuous camera feeds, with the three outward-looking cameras covering a wider angle outside the vehicle (to capture the external environment, including other road users), an inward-looking camera (to record the driver's face/eyes), a top-view camera (to capture the driver's manual activities), a low frame-rate cabin camera (to capture passenger presence), and a foot-camera (showing pedal use). Moreover, the cameras in UDRIVE recorded at a higher resolution than SHRP2′s cameras.

In both UDRIVE and SHRP2, the DAS was connected to the vehicle's CAN bus (when available, for a subset of SHRP2 vehicles CAN was not available) and logged signals from the CAN. The SHRP2 DAS logged the standard signals such as speed, brake-pedal activation, and steering-wheel angle (Campbell, 2012). UDRIVE had a collaboration with Renault and Volvo trucks which enabled access to additional CAN data unavailable to SHRP2 (turn indicator signal, wiper activity, and brake pressure, among others). Additionally, while UDRIVE collected CAN data in all cars, not all the vehicle models in the SHRP2 study collected CAN data.

Overall, the data collected in UDRIVE was more detailed than the data collected in the other studies, providing a more comprehensive view of what was happening inside and outside the vehicle. Of particular importance was the continuous identification of other road users—most importantly, of VRUs.

4.4. Sample size and composition

The UDRIVE sample differed in two important aspects from the sample in the non-European studies. First, sample size: the final UDRIVE dataset collected about 400 vehicle-years of data. The U.S. SHRP2 study has a much larger sample (around 3000 vehicle-years), whereas the Canadian and Australian studies have a smaller sample (around 200 vehicle years and 120 vehicle years, respectively). A larger sample facilitates the study of rare events such as crashes and generates a higher probability of getting statistically significant results. The UDRIVE dataset contains seven identified crashes, which is not enough for any generalizations. However, it does contain a large number of safety critical events which are often considered as a good proxy for real crashes.

Second, sample composition: whereas the sample of the non-European naturalistic driving studies consisted of passenger car drivers only, the UDRIVE study also included truck drivers and PTW riders. Both trucks and PTWs have safety problems different from those of passenger cars. In order to collect data from trucks and PTWs, the UDRIVE passenger car DAS was adapted to fit the vehicles. A strength of the UDRIVE data is that it is conducted with the same DASs and the same vehicle makes and models during the same time period, using the same data processing and analysis tools so that the data collected were directly comparable. This design reduced potential instrument biases, increasing the validity of result comparisons—for example, comparing when and how car and truck drivers check the blind spot, or when and how they engage in distracting behavior.

4.5. UDRIVE in relation to other naturalistic driving studies

Fig. 4 demonstrates how the four different studies relate to each other with regard to the key parameters of the study designs: the data collected and the sample size. The SHRP2 sample was substantially larger than the UDRIVE sample, but the data collected was less detailed. The Australian and Canadian studies have smaller samples than the UDRIVE study, and collect also less detailed data, though, by using smart cameras, the data are somewhat more detailed than the SHRP2 data.

4.6. Generalizability of the UDRIVE dataset

The generalizability of the UDRIVE data must be considered with care. The sample sizes, in particular those of the truck drivers and PTW riders, impose limitations. Furthermore, it was not possible to realize a sample with an age and gender distribution that reflected the distribution in the overall population; the distribution of other variables—such as income or education level—that might (directly or indirectly) influence driving behavior might also fail to represent the population's distribution. The dataset does include data from six European countries, but each country is represented by just 30 to 50 participants, limiting UDRIVE's usefulness for comparing different countries. In addition, the data's age and gender distributions varied between countries. In other words, the full UDRIVE sample is not necessarily representative of the European driver population, and the country samples are not necessarily representative of the countries' driver population.

Another factor that limits the generalizability of the UDRIVE dataset is the fact that all participating car drivers drove Renaults—either the Clio, representing the small-car segment, or the Megane, representing the medium-car segment. Together, these car segments accounted for 49% of the European Union passenger car market share in 2011 (Bärgman et al., 2017), but the fact remains that they were all made by a single manufacturer. A similar limitation applies to the generalizability of the truck and PTW results: the truck sample only included Volvo FM and FL models in the Netherlands, and the PTW findings only included the 125 cc Piaggio Liberty model in Spain (although this model has been one of the top five PTWs sold in Spain for the last ten years).

5. Conceptual framework for naturalistic driving studies

Naturalistic driving studies have the potential to address a wide range of research questions. Both the number and kind of variables measured (i.e., the DAS configuration) and the sample size and composition largely define the scope of the study and the type of research questions that can be studied. Fig. 5 conceptually demonstrates how the participant sample and the DAS configuration interact to define the scope of a naturalistic driving study, mapping out the type of research topics that can be investigated (see also Lotan et al., 2017). The figure presents a conceptual framework showing the relation between the key parameters of the study design, the sample selection and data acquisition system, and the scope of the study in term of research topics that could be investigated. The framework could be used for guiding decisions about the setup of naturalistic driving studies and/or selecting a suitable existing dataset to answer specific research questions.

To study frequent behaviors, a relatively small sample will provide enough relevant and representative data. Behaviors such as overtaking,

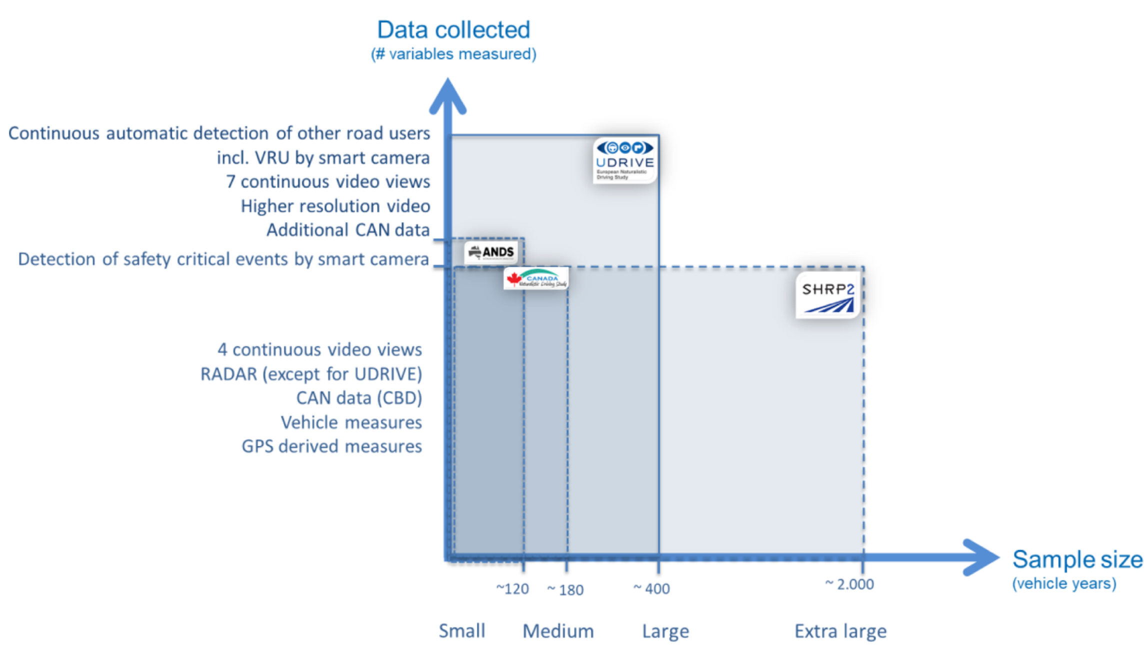

Fig. 4. Schematic presentation of differences in study design between UDRIVE and SHRP2 and the Australian and Canadian extensions.

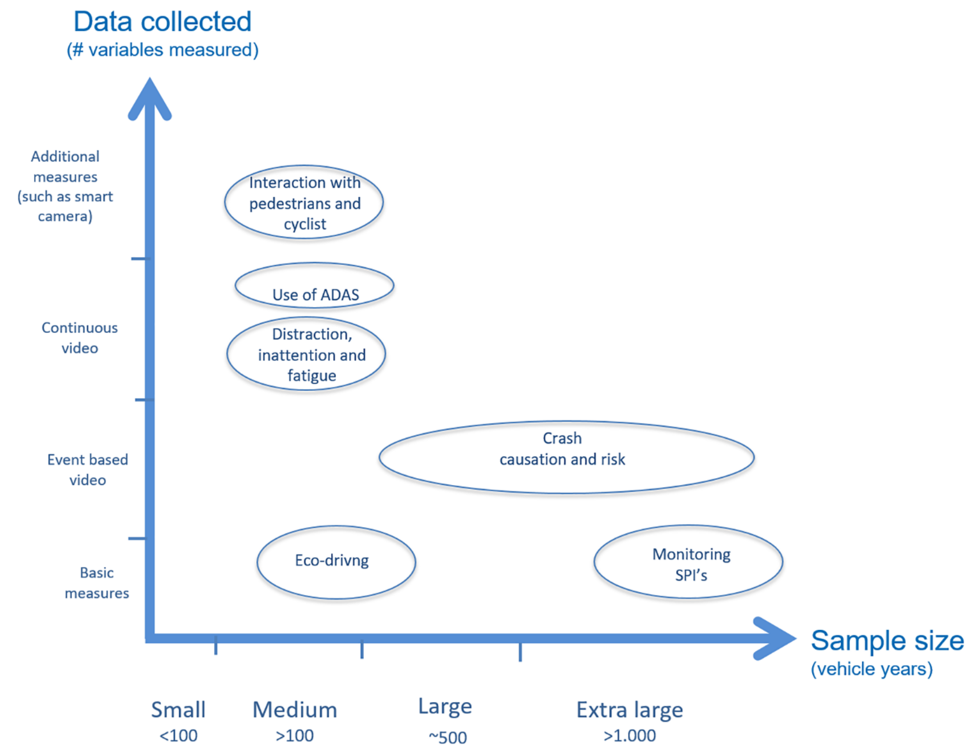

Fig. 5. Conceptual framework for naturalistic driving studies - the relation between DAS configuration, sample size and research topics.

navigating a roundabout, or turning right at an intersection will be present in almost every trip. In contrast, to study less frequent behaviors, much more data must be collected. For example, drowsiness or involvement in secondary tasks may not be observed in every trip, requiring more participants and more driving hours per participant to get a sufficient number of observations to study the topic. Similarly, to study actual crashes, which are very rare, data from a large number of kilometers (hours) need to be collected. If a specific type of crash is to be investigated, even more data is needed. In general, the rarer a situation one wants to study, the larger the sample needs to be to get enough relevant data.

If the DAS configuration merely records basic measures such as speed and GPS location (continuously or event-based), researchers can study topics such as speed behavior and route choices. To obtain a more complete appraisal of the situation and study more topics such as distraction and involvement in secondary tasks, cameras can be added to register what's happening inside and/or outside the vehicle. Clearly, as more variables are measured, a wider range of research questions can be studied. And, subsequently, the more detailed the information on the variables measured, the better the insight that researchers can get into drivers' behavior.

Decisions on sample size and DAS configuration both directly affect the costs of a naturalistic driving study: costs go up as the sample size becomes larger and the DAS more sophisticated. A larger sample costs more because it requires more equipment (DAS units), more participant incentives, more time and effort for participant recruitment and more time and effort for DAS installation and maintenance. A more sophisticated DAS unit costs more not only because advanced sensors (e.g., smart camera, radar) are more expensive, but also because measuring more complex variables (in particular video data) requires more data storage capacity and processing time. Decisions on the setup of a naturalistic driving study will therefore always require balancing the study ambitions against available resources. The consequences of the final decision are, however, far-reaching as it largely determines the research topics that can be studied.

6. Conclusion

The collection and analysis of naturalistic driving data are costly and time-consuming. However, the in-depth insights they provide into real driving behavior in real traffic can help us understand key concerns about road safety and eco-driving.

The new insights can inform the development of innovative and targeted measures to improve the safety and sustainability of our road traffic, leading to innovative policy measures and support for the evolving car industry. As illustrated in this paper, a detailed look "over the shoulder" of drivers in real traffic provides information that cannot be achieved with other methods.

Initial analyses of the UDRIVE data show that the differences across countries can be significant. Results found in one country do not necessarily apply to another, demonstrating the need for targeted regional studies. It is thus of great value to have a cross-European dataset, demonstrating differences within Europe, as well as between European countries and non-European countries such as the U.S., Canada, and Australia. Results from cross-country comparisons can be used to help national decision-makers address specific safety or eco-driving issues and help EU-level policy-makers set EU agendas and guidelines. Clearly, the large and comprehensive dataset offers the opportunity for many more analyses of a wide range of everyday driving behaviors.

Given the costs and time involved in the collection of naturalistic driving data, before collecting new naturalistic driving data it is worth checking whether existing data (e.g., UDRIVE, SHRP2) could be used. The analyses performed so far within the scope of the UDRIVE project have scarcely begun to exploit the database; and yet, the results already demonstrate the data's potential. Even though the project has ended, the data can still be used to gain new scientific insights into driving behavior. Combining multiple sources of naturalistic data—for example, the different databases mentioned—will make it possible to gain deeper insights into many of the research questions we cannot answer yet—including those questions related to driver differences across driver traits, driver states, and driving cultures.

Declaration of interest

None.

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The UDRIVE dataset is available for further research, for information about the data access you can contact the UDRIVE project coordinator and first author of this paper Nicole van Nes at Nicole.van.Nes@SWOV.nl.

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