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Effects of the driving context on the usage of Automated Driver Assistance Systems (ADAS) -Naturalistic Driving Study for ADAS evaluation

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ABSTRACT

Automated Driver Assistance Systems (ADAS) are designed to support the driver and enhance the driving experience. Due to ADAS limitations associated with the driving context, the intended use of ADAS functions is often non-transparent for the end-user. The system performance capabilities affected by the continuously changing driving context influence ADAS usage. However, the cumulative effect of the driving context on driver behavior and ADAS usage is insufficiently covered in the ongoing research. This paper aims to investigate and understand how the driving context affects the use of ADAS. Throughout this research, data from a Naturalistic Driving (ND) study was collected and analyzed. The analysis of the ND data helped to register how drivers use ADAS in different driving conditions and indicated several issues associated with ADAS usage. To be able to clarify the outcomes of quantitative sensor-based data analysis, an explanatory sequential mixed-method design was implemented. The method facilitated the subsequent design of qualitative in-depth interviews with the drivers. The combined data analysis allowed a holistic interpretation and evaluation of the findings regarding the effect of the driving context on ADAS usage. The findings warrant consideration of the driving context as a key factor enabling the effective development of ADAS functions.

1. Introduction

Automated Driver Assistance Systems (ADAS) are systems designed to assist the driver in the driving task and ensure more efficient and comfortable driving. The systems range from different types of information and warning systems to adaptive functions that offer longitudinal control of the vehicle through accelerating or braking in various traffic conditions, and/or lateral control through providing steering assistance (Young, 2012; Ziebinski et al., 2017).

These types of systems (although under different names) are today standard in, or are offered as an option by, most car manufacturers including Cadillac, Tesla and VOLVO Cars. VOLVO Cars' Adaptive Cruise Control (ACC) and Pilot Assist (PA) are examples of ADAS. Whereas the ACC uses vehicle cameras and radar to automatically adjust the vehicle's speed with regard to other objects moving in front, or keeps a set speed, the PA function offers the same functionalities as the ACC, but also supports lane keeping. Using the SAE classification (2018), ACC can be defined as Level 1 - Driver assistance, and PA, respectively, as Level 2 - Partial automation.

A pre-requisite for the desired effects of ADAS to emerge is that the systems must be used and they must be used in the way that is intended, taking into account the limitations of the system. According to information from the manufacturer, VOLVO's ACC and PA systems do not cover all driving situations, traffic, weather and/or road conditions. PA requires, for example, clear markings on the road in order to function. In addition, it is not recommended to be used in demanding driving conditions, such as city driving or other heavy traffic situations, in slippery conditions, when there is a great deal of water or slush on the road, during heavy rain or snow, during poor visibility, on winding roads, or on highway ramps (VOLVO Car Corporation, 2019).

The limitations of these and other ADAS may be well known to the manufacturers, and information may be available, for example in the instruction booklets of the vehicles, but studies of the degree to which drivers understand and take the limitations of the systems into account are, to the authors' knowledge, scarce. However, a recent study shows that a large proportion of drivers are unaware of, or do not fully understand, the limitations of different types of driving support systems (McDonald et al., 2018); results which underline the importance of investigating the issue further. Furthermore, the described limitations of ADAS are related to driving context, which is the summary of external factors that affect driver behavior while using the evaluated system (Zhai et al., 2018). For ADAS specifically,

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the driving context includes traffic, road and weather conditions which may, depending upon the drivers' understanding of the system, encourage or discourage ADAS usage. Several studies have emphasized the effect of driving context on driving behavior (e.g. Liang et al., 2016; Ahlström et al., 2018; Ahmed and Ghasemzadeh, 2018; Papazikou et al., 2017; Zhai et al., 2018), as well as on drivers' interaction with in-vehicle systems and nomadic devices (e.g. Tivesten and Dozza, 2014). Thus, drivers' use of ADAS needs to be investigated and understood with regard to the driving context, since there is clear evidence of its effect on driver behavior and system performance.

Studying driving behavior in context is a fundamental characteristic of Naturalistic Driving (ND) studies and Field Operational Tests, such as the 100-Car naturalistic driving study (Neale et al., 2005) and the MIT Autonomous Vehicle Technology (MIT-AVT) study (Fridman et al., 2019). ND study refers to a study where the data collection is not constrained by a strict experimental design, and where the data is gathered in a natural driving context and under various driving conditions, closely resembling real-driving situations. In this type of study, a large number of vehicles are equipped with data acquisition systems that continuously and inconspicuously register driver behavior, vehicle maneuvers, and external conditions over longer periods of time (see for example van Schagen and Sagberg, 2012). The EuroFOT (European Field Operational Test) (Benmimoun et al., 2013) and TeleFOT (Will et al., 2012) projects were designed particularly to assess the effects of different types of assisting and automated systems on driving behavior, including safety-related indicators such as speed, braking, time-headway, etc. (Benmimoun et al., 2013). Data on context or 'situational variables' such as weather conditions and road type were collected and conclusions were drawn regarding the context the systems were used in. However, a detailed in-depth analysis of the gathered vehicle data, assessing the cumulative effect of driving context, has not been reported to date. Thus, knowledge is lacking as to how driving context factors influence drivers' use of ADAS. Without an in-depth analysis of the complexity of the interactions between the driver and the ADAS under various driving contexts, an assessment of the collaboration between the driver and the evaluated system is incomplete (Fridman et al., 2019).

The mentioned research shows that in order to understand the drivers' usage of ADAS, the driving context needs to be taken in consideration regarding the evaluated ADAS functions. These results have encouraged OEMs to improve vehicle sensors data (Tornell et al., 2015), which opens the possibility to assess the driving context quantitatively and include it into the overall ADAS evaluation. Therefore, the aim of this paper is to pursue an understanding of how the driving context affects the use of ADAS and to facilitate by means of an ND study a sensor-based data collection combined with in-depth interviews. Such knowledge can contribute to the further development of ADAS to fit different use contexts.

2. Method

An Explanatory Sequential Mixed Methods (Creswell, 2014) approach was adopted and modified to fit with the scope of this research. The sequential use of quantitative and qualitative approaches (see Fig. 1) aims to facilitate an integrated interpretation regarding the effect of the driving context on ADAS usage.

The explanatory sequential design had two distinct phases. During the first phase, quantitative data was collected, analyzed. Prior to this step

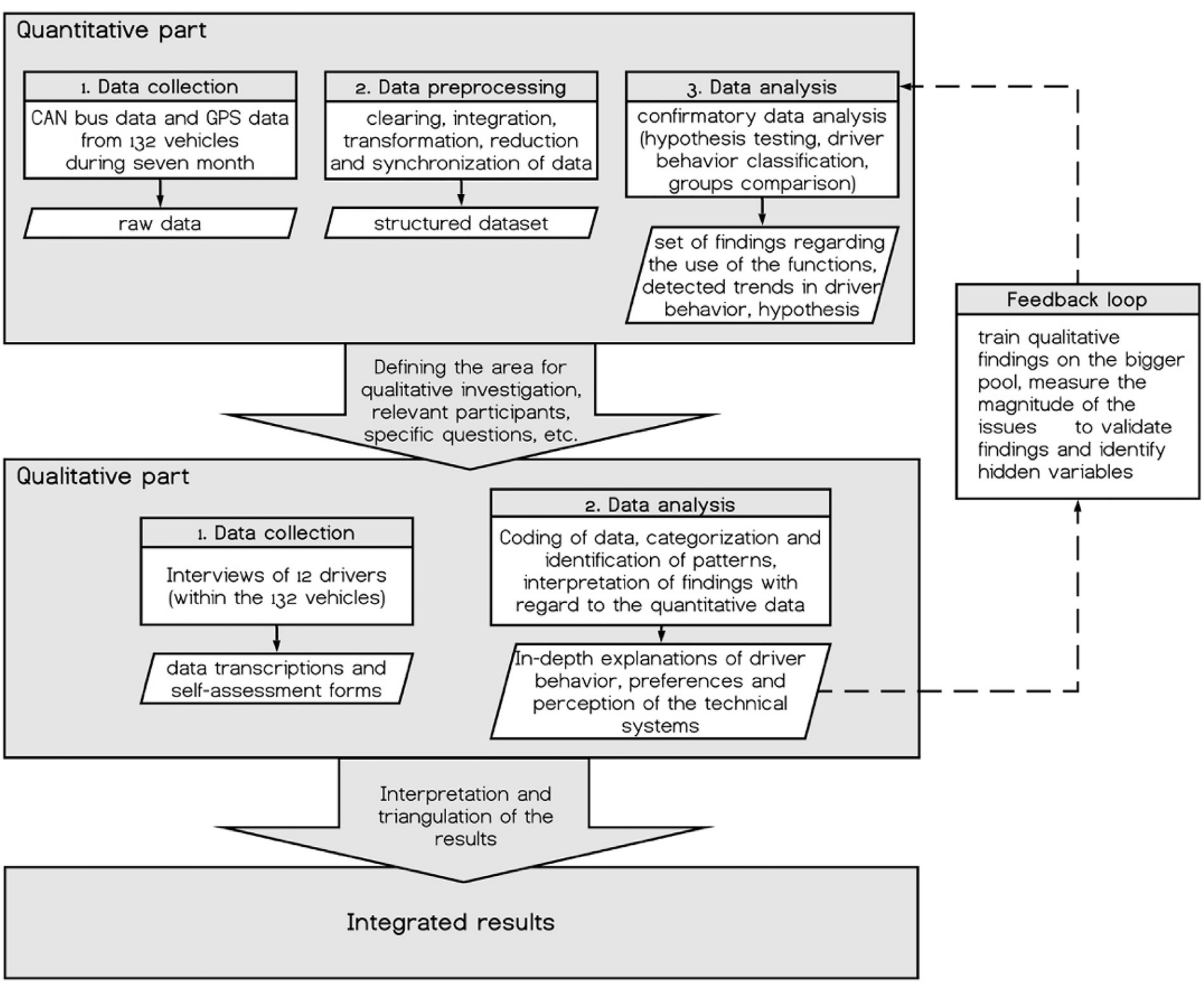

Fig. 1. Explanatory sequential mixed methods design.

objectives and relevant measuring parameters were defined, and evaluation questions were set. To collect the quantitative data a ND study was utilized.

In the course of quantitative study, performance data for both the driver and system were measured together with contextual information including the weather conditions, the road conditions, and the data indicating the traffic conditions on the roads.

The ND data in this study enabled a time-efficient and reliable way for in-depth quantitative driving context evaluation, in combination with a system and driver performance assessment. The data analysis was carried out with a focus on the defined objectives and questions formulated beforehand. The level of usage, the detection of usability issues, and the identification of various trends and patterns in driver behavior were addressed.

To be able to clarify the sensor-based findings, in-depth interviews with the study participants were subsequently carried out, aiming to explain and uncover the effect the driving context has on the system usage. The subsequent design of the qualitative phase was designed so that the qualitative study built on the results of the quantitative phase and explained emerging phenomena. The qualitative study design, therefore, was focused on the clarification of the subjective reasoning of the drivers, inside the detected target groups, in order to understand the specific user behavior and driver needs and be able to map out the interdependencies that influence the system usage. Respondents for the qualitative study were chosen from drivers of the vehicles involved in the quantitative phase.

The purpose of the triangulation was to revise the completeness of the quantitative dataset. The triangulation of qualitative insights into the quantitative findings helped to track specific data-variables that were detected during the qualitative study but were not measured at the quantitative level (e.g., sensors data that supports the assessment of oncoming traffic). Thus, the identification of hidden data variables that could be included in the quantitative evaluation helps to enhance the quality of the quantitative assessment in future studies.

Moreover, the feedback loop of the qualitative findings was utilized for further investigations at the quantitative level. The qualitative insights were tested on a wide range of users, aiming to verify the validity of the qualitative explanations, i.e. to check if the statement applies every time in the same driving conditions. The purpose of this step was to see if the qualitative insights that users gave through the in-depth interviews could be generalized.

The quantitative and qualitative data in this study was collected with the informed consent of all drivers, regarding all collected data points, and their preceding agreement to participate in this research project. The retrieval, storage and processing of the collected data was accomplished strictly according to the European general data protection regulations (GDPR). The data was processed confidentially and all participant identities were kept strictly anonymous.

2.1. Quantitative study

Quantitative evaluation in this study provided precise measurements of driver and system performance in various driving conditions. The ND data helped to identify different use patterns regarding the evaluated functions and indicated some trends in driver behavior.

2.1.1. Participants

Drivers from 132 vehicles were participating in the quantitative study. All drivers used the vehicle as a primary vehicle for the full range of activities, including the commute to work, weekend trips, vacation, and all other possible driving activities. The previous driver experience and the time drivers needed to familiarize themselves with the ADAS were not considered. Since, in this study, we were primely focused on usage, not learning, we deliberately invited drivers with different levels of experience regarding ADAS functions, trying to replicate the real market. Moreover, before the measuring process started, all drivers got around three extra weeks of introduction driving where they can use vehicles freely, tried new systems, and get familiar with it. All participants were Volvo Cars employees, while no participant who was part of the development of the functions was accepted for the interview study.

2.1.2. Study design and procedure

For the quantitative data collection, data from 132 vehicles was collected and subsequently analyzed. All vehicles have the same version of the evaluated systems ACC and PA, but vehicle models vary and include 6 different Volvo car models.

Driver behavior and system performance were categorized and measured to be able to evaluate these separately and see their effects on each other. Data variables that enabled the understanding of ADAS usage, (e.g., vehicle speed, driving distance, type of driving activity, date of the event, time of the day the activity happened, and others) were derived from the ADAS abilities and limitations, described by ADAS developers (Volvo cars, 2019). Since the use of ADAS is initially designed for longer DCs and better performs on high-ways with dense traffic, these additional parameters affecting the use of ADAS were identified and used.

Data variables that enabled the understanding of the driving context for ADAS were also included in the assessment, e.g., GPS data, wiper sensors status, data for road conditions identification, data indicated traffic conditions, and other sensors data. The analysis of this data supported the possibility to conclude in what context the driver performed activations or deactivations of the ADAS functions. The data collection phase of this study was conducted over seven months, from April to October 2018. Table 1 describes context variables that were measured to assess weather, road and traffic conditions on the road.

Table 1
Summary of context variables for the ADAS driving context assessment.

Traffic condition variables	Description
Speed limits	To identify the allowed speed (km/h)
Driving speed	To see the deviation from speed limits (km/h)
Braking/acceleration	To determine the distance between changes (frequency)
Time of activ./deactiv.	To consider possible rush hour (t, h)
Data	To distinguish the workday from the weekend/holidays etc.
GPS location	To clarify the traffic conditions in historical data (Latitude/Longitude)
Road condition variables	Description
Ambient temperature	To exclude slippery road conditions (-2 °C $< t > 2$ °C)
Lane marks reading	To secure ADAS performance on the road (on/off)
Speed limits	To identify the road type (km/h)
GPS location	To consider issues like a crossing of the country borders, big road constructions, etc. (Latitude/Longitude)
Weather condition variables	Description
Wiping status	To detect heavy rain or snow: wiper statuses 5–7 (overall range 0–7)
Fog illumination	To control bad visibility conditions (e.g. fog, mist) (on/off)
Ambient temperature	To clarify precipitation (t,°C)
Data	To record the seasonal change
GPS location	To clarify the weather conditions in historical data (latitude/longitude)

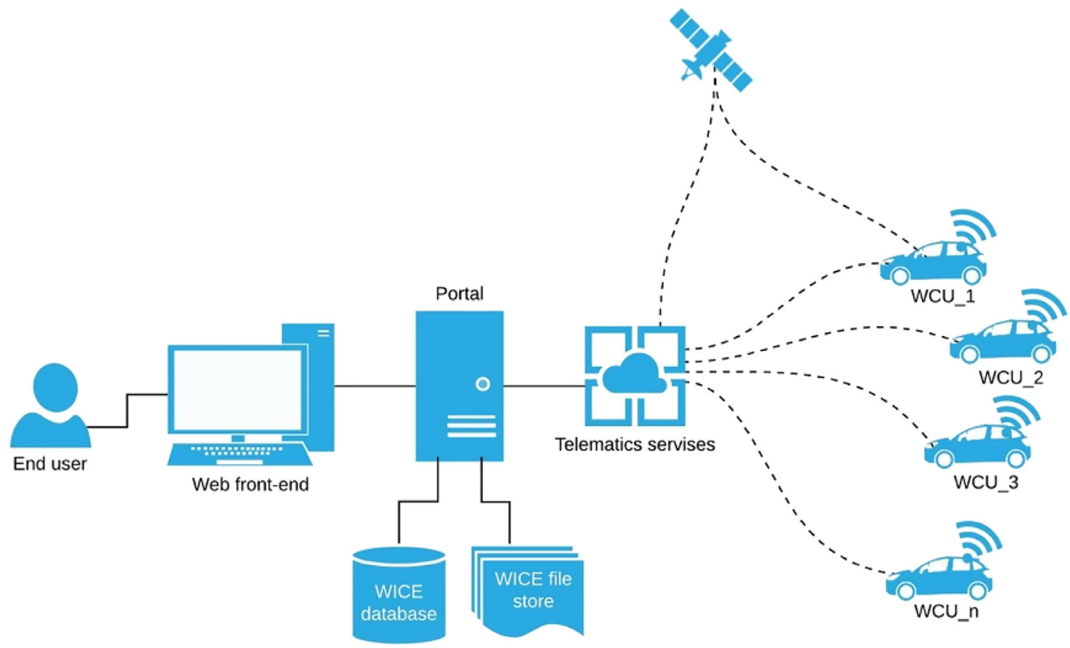

Fig. 2. A high-level overview of the WICE-system communication infrastructure.

2.1.3. Data retrieval and data pre-processing

The data collection was conducted using the WICE system. The WICE system is an external wireless communication and data acquisition unit that was installed in every test vehicle. The WICE system enabled the management of the data from the vehicle fleet, by keeping track of map-based positioning, mileage, uptime and diagnostic codes. Fig. 2 shows the high-level architecture for WICE data logging and the real-time data processing system.

The raw data consisted of data from the Controller Area Network and the GPS data and was collected for every Drive Cycle (DC). By single DC we mean one driving activity that starts with the start of the engine and ends with the engine shutdown. All DCs, including DCs with no data, were included in the evaluation. Every DC was recorded and documented with a unique file-name to be able to connect the vehicle to its data and evaluate at a later stage.

In the data pre-processing step, all corrupt and inaccurate records were removed from the dataset. The data was synchronized in time, providing the order and structure for the initial dataset.

2.1.4. Data analysis

For the main phase of the quantitative analysis, a confirmatory approach was adopted with the aim of clarifying the importance of the driving context for the ADAS usage and effect on driver behavior. The data analysis was conducted with Power BI software for statistical analysis (Power BI Microsoft, 2019). The data was analyzed in four different layers of abstraction: single DC evaluation layer (if something indicated unusual or interesting user behavior that needed in-depth investigation), one-driver evaluation layer (focused on in-depth user behavior evaluation of the same driver), groups comparison layer (based on the comparison of user behavior between different user groups), and overall assessment layer (based on the average calculation for all users).

2.1.4.1. Single DC evaluation. All data was collected and recorded by the WICE data acquisition system on a trip basis. This means that it was possible to evaluate every DC individually, using in-depth analysis of how the driver behavior changed in relation to the different driving contexts. Fig. 3 presents an example of a single DC evaluation layer, where the GPS points for a trip are shown, as well as the function used on this particular trip. Additional variables describing driving context, e.g. the speed used during the DC, the traffic, and road or weather conditions, can be added to support the general understanding of the assessed trip.

2.1.4.2. One-driver evaluation. The one-driver evaluation layer provided the possibility to assess the overall driver behavior through the calculation of average key parameters for user performance in different driving conditions. The possible key parameters that can be chosen are the total measurement time, activation duration time, activation duration distance, time of activation, DC type, road type, vehicle speed and others. The analysis of these parameters gave the overall impression of the way a particular driver used the function in various conditions. Fig. 4, for example, illustrates how the driver used ACC and PA depending on the DC length, chosen speed, and time of the day. The one-driver evaluation layer helped to understand what driving activities were more common for the driver and how those activities correlated with the usage of the ADAS.

2.1.4.3. Groups comparison. The knowledge about the overall behavior of a particular driver allowed the drivers with similar behavior to be identified and categorized into different groups. Further, the driver categorization was used to compare the driving behavior in different geographical markets or to make comparisons between other identified groups. Fig. 5, for example, indicates the different use of ACC and PA between drivers in different markets. The main question for the group comparison was to understand what the key differences between the groups were and why two groups of drivers had been using ADAS differently. For this purpose, a combination of variables was used indicating how driving conditions for those two groups differed, including the GPS-location that shows in what area the driving activities of those groups had been happening.

In general, the ND data analysis allowed precise and reliable results to be achieved. Moreover, quantitative data analysis enabled the understanding of the severity of detected issues by checking the number of vehicles, or the number of DCs that accounted for the same problem.

2.2. Qualitative study

Subsequently, in-depth interviews were conducted to receive explanations and reflections on the recorded driver behavior during the ND study. This helped to uncover the human factors affecting driver behavior and system usage.

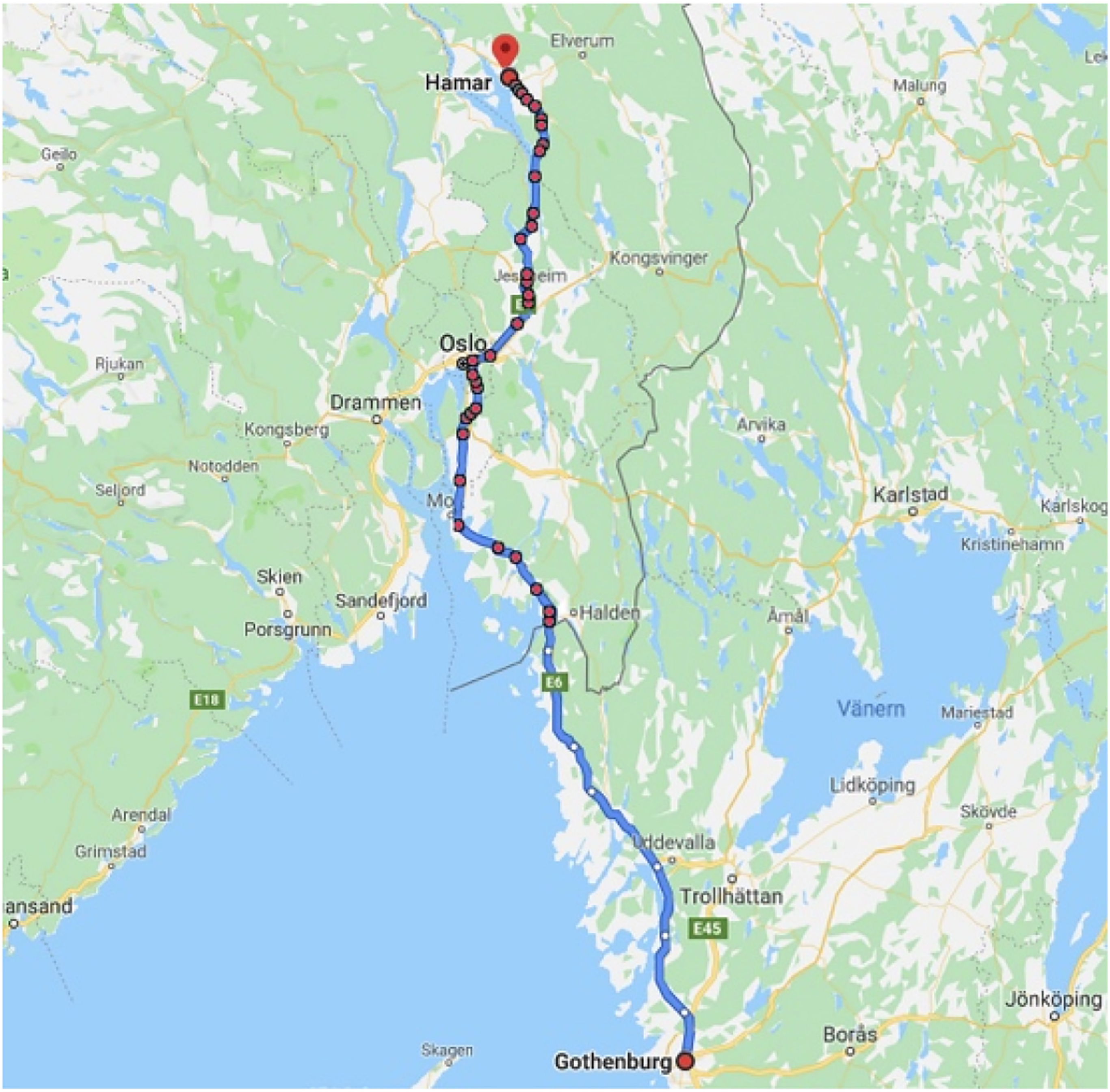

Fig. 3. Visualization of one selected DC, based on GPS data and ACC activations.

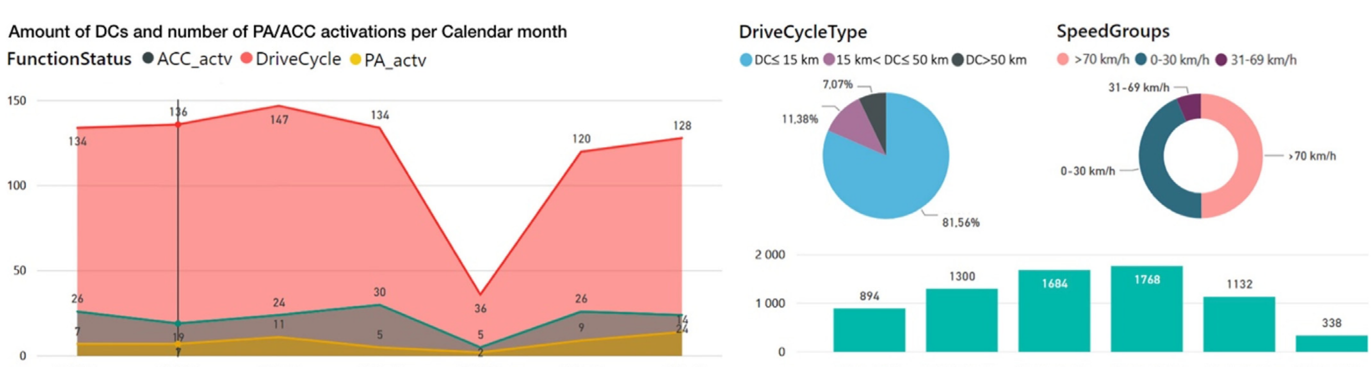

Fig. 4. Example of data variables for one-driver evaluation.

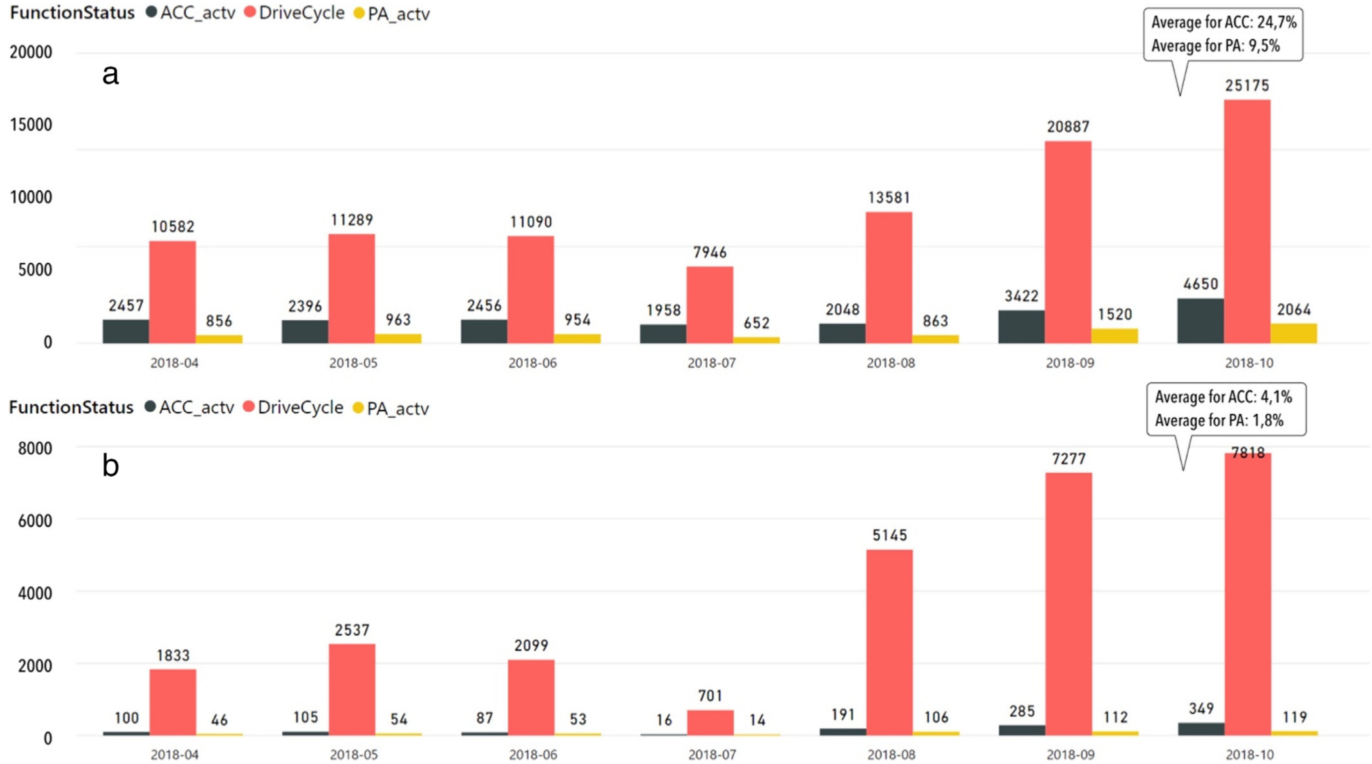

Fig. 5. Comparison of two group behavior regarding ADAS usage: a) in Swedish market (up); b) in Chinese market (down).

2.2.1. Participants

The interview study consisted of 12 participants, 2 female and 10 male, with an age range of 31–62 years (Mean 52.4, SD = 9.0). The participants were recruited via an email newsletter, which was directed only at members of the WICE vehicle group and only at the participants of the quantitative study. Thus, every interested member who took part in the qualitative study and was located in Gothenburg was potentially a valid participant.

All participants were commuting every day, 5 participants were accounting for an annual mileage of >30,000 km, 4 participants drove between 20,001 km to 30,000 km per year, and 3 between 10,001 km and 20,000 km. All participants who drove vehicles registered in the WICE study were long term users of VOLVO vehicles and were familiar with current functions or support systems of the previous generation. From the quantitative data collection, it was known that participants had a different level of usage and engagement with the systems. According to their own estimation, 9 of the participants were the sole or main drivers, sharing the vehicle only 0–10% of the total driving time. Two drivers were sharing the vehicle up to 20% of the time, and one driver up to 35% of the total driving time.

2.2.2. Study design and procedure

The investigation and validation of the quantitative data was done by means of in-depth semi-structured interviews to explore the individual experience and understanding of the systems. Interviews as a data collection method are a valid and reliable choice in aiming to obtain knowledge about driving behavior, user perception and the users' mental model of the driver assistance system (Beggiato and Krems, 2013).

The interview study was conducted between December 2018 and February 2019. All interviews were audio-recorded with the participants' consent. The interview comprised of four parts: Contextual Information; System Usage and Scenarios; Perception and Experience with the System; Information Display and Controls. Thus, a set of open-ended questions was developed, based on the four main themes. The structure of the interview and the interview questions were based on the initial results of the quantitative study. The interview was conducted using the developed topic guide, and all respondents were asked the same set of questions. However, the interview was not limited to the sample questions and the participants were encouraged to elaborate on their experiences and provide more descriptive insights.

In addition, a questionnaire aimed at self-assessment of the usage of ADAS in different driving contexts was handed out to the participants after the interview. The questionnaire consisted of Likert type (Likert, 1932) scenario-based statements with four response categories, without a neutral category. Finally, the participants' background information, including age, gender, car model and year, commute behavior and kilometers driven per year, was mapped. All sessions were conducted individually, face to face and in English.

Each session lasted about 1 h, including interview and questionnaires. The participants were reimbursed with a cinema voucher for attending the interview.

2.2.3. Interview analysis

All interviews were carefully transcribed verbatim, coded and analyzed with the software NVivo 12. The first transcript was analyzed by both researchers in cooperation, by first categorizing the transcripts into the corresponding topics and questions. Since the interview structure and content was based upon the initial results of the quantitative analysis, the categories were already determined, leaving the researchers to identify different themes and their meanings within the categories. In the next step, the themes were reviewed and discussed in order to determine coherence and reliability. Afterwards, the interviews were coded by each researcher separately and a final session was held, where open questions and themes were discussed to review the quality of the coding.

2.3. Integrated analysis

During the analysis of the quantitative results different issues were identified, which guided the qualitative analysis. Moreover, when the 12 drivers agreed to participate in the qualitative study, their usage of ADAS function was inspected from already collected data. According to this data (see Fig. 6), the grade of use for ACC and PA among 12 respondents varied from nearly “No usage” (vehicle 20) to “High-level usage” (vehicles 19, 28,197) and

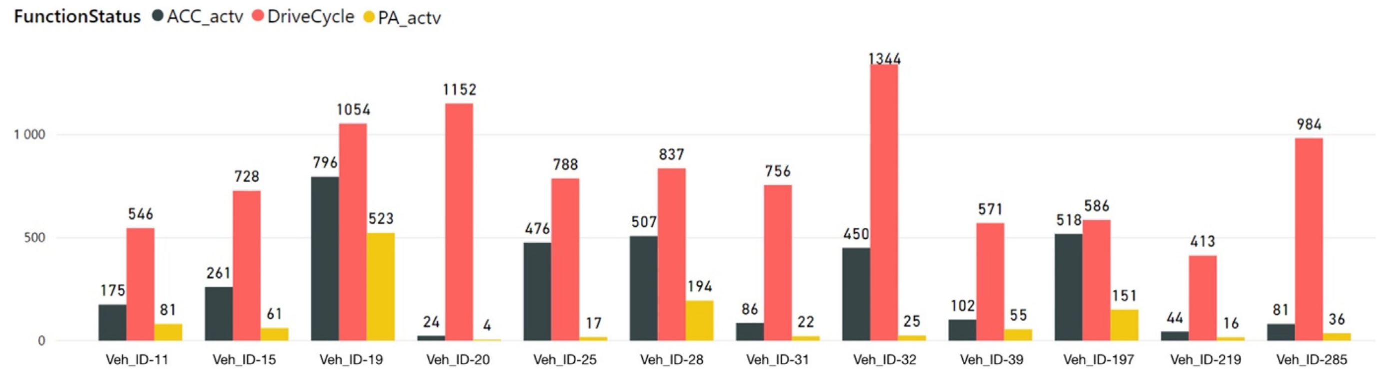

Fig. 6. The grade of usage for ACC and PA from 12 interviewees.

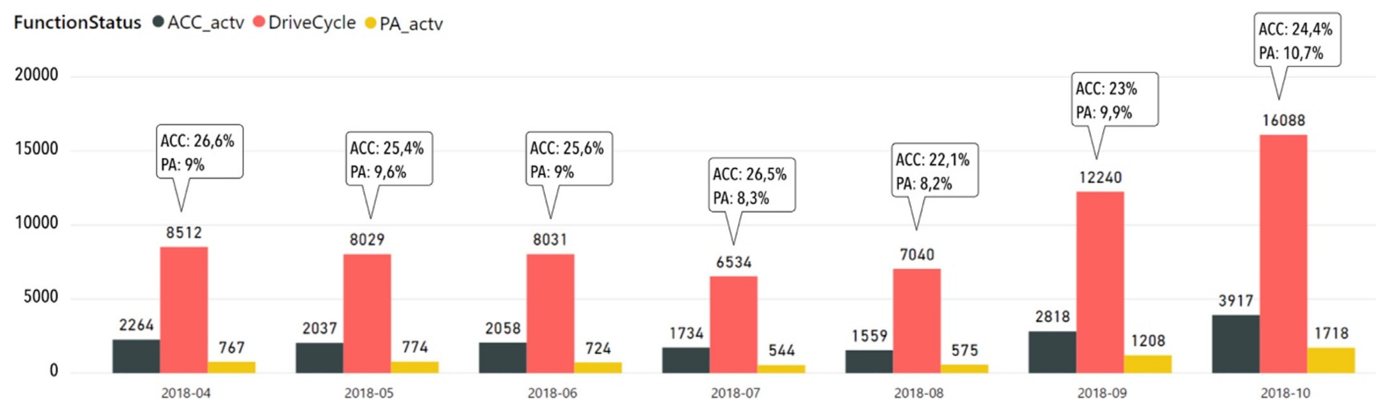

Fig. 7. Average per month of PA and ACC usage for 132 evaluated vehicles.

represented all groups of driver behavior identified during quantitative analysis. This wide distribution of drivers regarding ADAS systems usage ensured the possibility to contribute with qualitative explanations for all designated groups.

After transcription of the interviews, statements where participants described their use of the ADAS functions ACC and PA were extracted. This helped to explain the sensory-based observations and identify relevant aspects of the driving context influencing the drivers' usage of ADAS.

For the evaluation of the results a deductive coding approach was applied, correlating with the predetermined framework from the quantitative data evaluation and interview structure. This sought to investigate if the identified trends from the qualitative study were supported by the qualitative data. An inductive approach was also applied in the next step to assess the themes and discover new insights beyond the quantitative results that were not covered by the initial analysis.

The analysis resulted in three themes: Driver Categorization, Use Contexts, and Perceived System Performance, of which two (the Driver Categorization and the Use Contexts), were based on the quantitative analysis results. The theme of Perceived System Performance emerged as a complementary theme, contributing to the explanation of many phenomena detected during the analysis of the other themes.

3. Findings

This chapter describes the synthesis and analysis of the quantitative and qualitative findings, aimed at understanding how the driving context affects the use of ADAS.

3.1. Driver categorization

In a first step, it was assessed with a high level of precision how ACC and PA were used by the drivers from 132 vehicles. The average use of ACC and PA was calculated based on seven months of fleet measurements. The average for the ACC usage was 24.7% of all DCs, and the average for the PA usage was 9.5% of all DCs. Fig. 7 graphically represents these results.

However, these numbers do not represent each and every driver. The one-driver evaluation layer showed that there are drivers who do not use the systems, and there are those who use the systems to a high extent. Moreover, there is no defined use level for ADAS functions that developers expect from drivers. Thus, taking average as a nominal, the average range from $\geq -5\%$ to $\leq 5\%$ was set. This was done to exclude the drivers closed to the average from observation of the extreme groups. The investigation of how the drivers from the extreme groups handle the dynamically changing driving context and what are the differences in their driver behavior patterns was in focus. Thus, the individual driver performance was precisely measured, and four user groups were defined based on the level of ACC and PA, as can be seen in Table 2.

The “No usage” group consists of drivers who are not using PA and/or ACC regularly; 0–4 activations detected for every respective driver in the group for the whole period. The “Low-level usage” group consists of drivers who use PA or both functions up to 5% below the average of the complete pool of drivers. The “Middle-level usage” group consists of drivers who use PA or both functions in the range from $\geq -5\%$ to $\leq 5\%$, of the average of the complete

Table 2
Definition and classification of user groups, based on the use level of ACC and PA.

Group	Used range	Description
No usage	0% (max 2 activations detected)	10 drivers (7,6%)
Low-level usage	5% lower of average	52 drivers (39,4%)
Middle-level usage	±5% around average	46 drivers (34,8%)
High-level usage	5% higher of average	24 drivers (18,2%)
Total		**132 drivers**

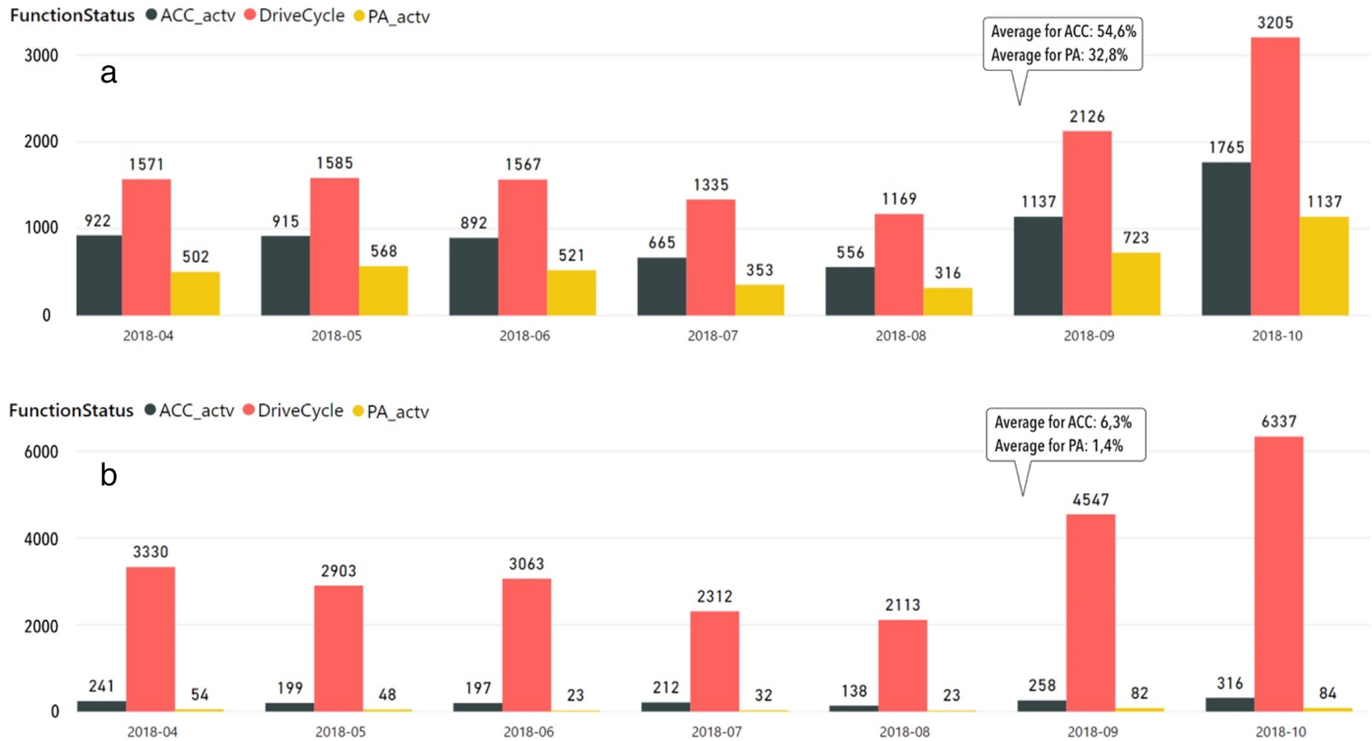

Fig. 8. Comparison of user behavior by the grade of usage of the evaluated function: a) Group of users with a high-level usage of the functions. b) Group of users with a low-level usage of the functions.

pool. The "High-level usage" group consists of drivers who use both functions at least 5% above the average of the complete drivers' pool.

In the next step, the system use grade of the "Low-level usage" and "High-level usage" groups was compared and evaluated according to the driving context in which PA and ACC were used. This focused on identifying the key differences in the driving conditions between the two groups. Fig. 8 illustrates the differences in the grade of ACC and PA usage between those groups. The average for the "High-level usage" group (see Fig. 8a) shows an extensive function use with an average of 54.6% of total DCs for ACC and 32.8% of total DCs for PA. The numbers for the "Low-level usage" group are significantly lower (see Fig. 8b). ACC is only used in up to 6.3% of all DCs and PA is used in up to 1.4% of all DCs.

Despite the significant difference in the usage grade for both ADAS functions, from the driving context perspective, both groups operated under similar driving conditions. Moreover, the weather and geographical area were the same for all drivers, since the measurements were taken on the same dates and in the same region. However, the road and traffic conditions varied, dependent on the residence area of every participant, driving time, eventual road works and traffic congestion on some roads. Thus, it became clear that the driving context, especially the road and traffic conditions, can have a significant effect on the use scenarios that two groups chose for ADAS usage. Therefore, the focus of the following section is further analysis of the use contexts for ADAS functions accepted by drivers from different groups.

3.2. Use contexts

A clear trend regarding the usage of the function on varying DC lengths could be observed from the quantitative data. The distribution of short, long, and medium DCs in driving activities was unequal. To illustrate this, all DCs were categorized into three groups: 1. Short DCs: ≤ 15 km, 2. medium DCs: 15 km < DC ≤ 50 km, 3. long DCs: > 50 km. It was found that the everyday driving activity for all drivers consisted mostly of short DCs, which accounted for 73.7% of the total driving activities (see Fig. 9), with long DCs performed occasionally, accounting for 6.6%.

The quantitative data also indicated a specific trend in user behavior regarding the engagement with the ADAS functions. A higher usage grade of ACC and PA was identified in the long DCs compared to short DCs. Fig. 10 shows that the usage of PA in long DCs exceeds the usage of PA in short DCs

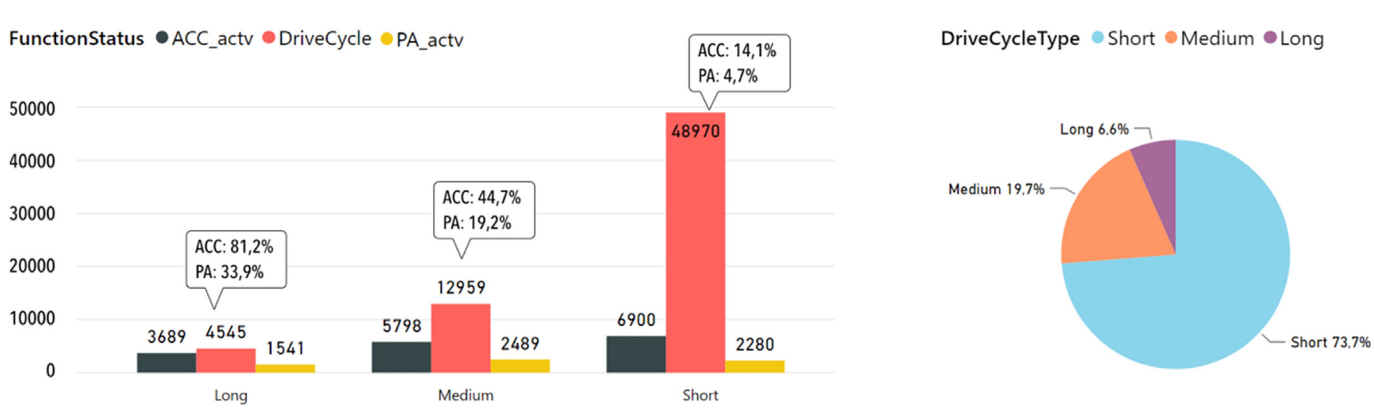

Fig. 9. Average use level of ACC and PA on short, medium and long DCs.

Fig. 10. ACC and PA usage in limited driving conditions: at low speeds (0–30 km/h) and on shorter trips (0–15 km) a) for drivers from the "High-level usage" group. b) for drivers from the "Low-level usage" group.

seven fold, resulting in 33.9% of all DCs for long and 4.7% for short DCs. ACC usage in long and short DCs showed a similar trend, with 81.2% of all DCs for long and 14.1% for short DCs.

This finding shows that the "Low-use level" can be explained by unequal distribution of short, medium and long DCs. Although the data showed the extensive use of ADAS in long DCs, the majority of driving activities were short DCs where the use of the ADAS was minimal. Further, the quantitative data shows that the drivers tend to activate the functions on long DCs within the first 15 km, which they normally do not do if they drive only 15 km or less.

During the interviews the 12 participants confirmed these results when stating that they tend to use the systems more on longer trips, e.g. driving a longer stretch to a holiday destination.

"I might sometimes not use it at all if it is a very short distance."

"But for longer trips I use it always."

In summary, there was an evident consensus on the advantages of using the systems during long drives compared to short drives. Especially ACC was named throughout the interviews as a great support during long drives regarding speed maintenance, an extra safety buffer and comfort.

Another parameter indicating the importance of the driving context is the activation duration time. To illustrate the relation between activation duration time and PA usage, four long DCs conducted by one driver were analyzed. Table 3 shows the activation duration time compared to the total driving time, and the number of PA activations for each of the four chosen DCs.

As can be seen in Table 3, even the driver's intention to use PA did not necessarily lead to a function usage. In DC 5301, the driver attempted to activate the function four times, which indicates his intention to use PA during this trip. If the first request to activate PA indicates the moment of driver intention to use the function, then the time when the PA could be used equals 72:03 min for DC 5301. However, the activation duration time in this DC was only 45:57 min. These results indicate that the driving conditions during the rest of the trip were considered inappropriate for PA usage.

During the interviews the participants stated several reasons for unsuitable conditions with regard to PA activation. In addition to the traffic conditions mentioned above, the road conditions were named as another factor influencing the system usage. Country roads were often considered unsuitable to fulfil the activation preconditions, and therefore, the drivers tended to not even try to engage the system when driving in the countryside. The reason why this was mentioned as a critical context was that country roads often do not have clear lane markings, resulting in the system jumping between active and stand-by, which is also the case during bad weather or bad light conditions.

Table 3
PA activation duration time compared to the total driving time for 4 DCs.

Drive Cycle ID	Number of PA act.	Drive Cycle Start time	First activation Start time	Drive Cycle Stop time	Activation Duration time, min	Total Driving time, min
5301	4	16:42:09	17:06:51	18:18:54	45,57	96,76
5470	2	15:40:14	15:46:03	16:13:09	21,26	32,92
5293	4	11:33:06	11:49:35	12:28:01	35,11	54,92

"It is the same roads I'm going on and I know where it doesn't work. You learn the way the car behaves by driving every day."

"The conditions that we don't have in Gothenburg, when it is snowy and the car gets really dirty and sensors get blocked and you don't have the support."

More specifically, it was widely mentioned that the preferred usage of the functions were *"on open road", "highways" or "when traffic was more in a flow."* The reason named for this was that in more urbanized areas frequent braking and driver engagement is needed, due to the infrastructure or other traffic participants, requiring the driver to activate and deactivate the systems too much.

"In the roundabout I need to either decrease speed manually with this steering wheel switch or I need to put the foot on the break in order to adapt to the speed, and it's also often so that I'm getting close to bicycle passages, or pedestrians passing. So I need to brake anyhow in order to stop. So it is not convenient to use the function in that area."

Furthermore, it was mentioned that country roads tend to be curvy, which the users do not consider to be conditions that the system is able to handle.

"If we start talking about PA, the limitation for PA is when driving on country roads. It is excellent when driving on highways or when you don't have sharp turns or whatever."

The findings and the statements clearly show that there is a learning curve to understanding when the PA function is available and reliable. Subsequently, one can argue that the usage seems to be connected to different road types, as well as weather conditions, which both influence system performance.

The above findings support the idea that all driving context parameters need to be considered in relationship to each other, as they comprehensively describe the driving event and are linked to the different situations drivers face during their everyday driving activities. To support this idea, an in-depth DCs investigation of how drivers behaved during specific trips was conducted. It was found that drivers had been using the ADAS not only on highways, where the driving conditions are most of the time reasonably good for the function usage. The quantitative data analysis showed that drivers with a "High-level usage" more often had been using PA and ACC at low speeds (0–30 km/h), on shorter trips (0–15 km) or on smaller roads, where the road curvature could be higher, and the speed restrictions lower. At the same time, the drivers with "Low-level usage" had more often been following the initial recommendations for PA, using it mostly on highways where the conditions for proper system performance are the best. Fig. 10 shows the difference in ACC and PA usage between the "High-level usage" (see Fig. 10a) and the "Low-level usage" (see Fig. 10b) groups in limited driving conditions, in particular at low speeds (0–30 km/h) and on shorter trips (0–15 km).

As we can see from the charts in Fig. 10, drivers from the "High-level usage" group were able to identify non-ideal conditions for systems usage and had been using the system in situations far from the ideal of intended use. The average for the group was 5.0% of all DCs for PA and 9.6% for ACC. The drivers from the "Low-level usage" group had come close to the "No usage" grade when the conditions were poor, with an average of 0.1% of all DCs for PA and 0.5% for ACC.

This finding correlates with the statements of the respondents who preferred using PA in queuing situations, or at lower speeds, as the steering behavior at lower speeds was considered more constant.

"Pilot Assist is doing this job at its best when it's stop and start."

"I put in the PA and then I don't need to take care of anything basically."

"Pilot Assist is limited to highways, when there are several lanes to drive in, and also when the speed is not that high."

The usage during short drive cycles or on country roads could not be confirmed through the participants' statements. However, these findings clearly show that the system performance and the driving context are closely interlinked, and therefore it is necessary to more thoroughly examine how the system performance influences the engagement of the drivers with the system.

3.3. Perceived system performance

During the interviews, the respondents mentioned different examples of when the functions did not act as expected, which put them in uncomfortable situations. It became clear that the attitude towards ADAS is affected by the system performance.

For example, the steering support of PA was widely not considered steady, so the drivers were also more reluctant to engage with it. Another issue reported for the steering support was that it felt like more effort than steering by themselves, since the system requires a constant torque on the steering wheel, which most of the drivers feel is more than they would apply while steering themselves, and therefore makes the system uncomfortable to use.

"You need to touch the steering wheel every 10 seconds or so, makes it a bit annoying maybe. At the same time I feel that you can take your hands completely off from the steering wheel. It is not really convenient."

As mentioned before, the lane keeping behavior of Pilot Assist is perceived as a concern. The users report that the system does not follow the lanes smoothly, because the system tends to correct vehicle position too much, causing an unsteady ride.

"It doesn't take you as smooth as you want to go. It corrects. You can be on a stretch that seems to be straight, but of course it is not. But it seems to be straight. And then it corrects the car to go exactly straight and that is not necessary. Because if you wait 200 meters then it turns the other way. So it is more convenient to let the car drift instead of being positioned correctly all the time."

The lane keeping behavior of the system is also an issue on curvy roads, where the respondents explained that the car's positioning in the lane made them feel uncomfortable or even unsafe, because they feared the car would not be able to take the curve. This feeling caused the drivers to disengage the system for the road conditions they considered unsuitable.

"If the road is maybe a little bit curvy, it could be that I switch it off due to comfort, because you sense the car…it's not following the road smooth. If you sense that then I usually switch it off until you have a calmer, straighter part of the road and activate it again."

Another behavior that the respondents described as not suitable to their needs was the time gap interval of ACC. Especially during rush hours a lot of traffic is experienced and the time gap interval seems to invite other traffic participants to cut in front.

"The distance to the car in front of you is too long because you leave such a gap that it's very easy to get in from the left or right lane. And then your car brakes, and then you create a new gap, and then comes a new car and so on…".

This behavior is not desired by the drivers, and caused them to override the system or deactivate it completely and drive themselves in those situations, to avoid falling back too much.

Another issue which was reported to cause discomfort was when the vehicle conducts an action the drivers did not anticipate. Two situations could be identified throughout all interviews.

The first situation many of the respondents described, was the vehicle accelerating when the driver did not expect that, because the traffic situation called for another action.

"It was accelerating when I wanted to decelerate, and it was maybe one or two seconds before I got control over it again."

"If it is a traffic light there and the vehicle in front is turning to the left, why should we accelerate?"

These examples were connected to the situations where the vehicle in front, which the car was following and adopting its speed to, disappeared and the speed settings of the ACC or PA called for an acceleration to the set speed. The drivers' statements indicate the difference between how the system and driver recognize the context. The system is not always capable of anticipating the drivers' intention, but the drivers seem to expect a system that acts smarter and reads the current traffic situation, e.g. traffic lights or other traffic participants.

"It has a lack of forward looking capability or so. That it really sometimes does stuff which totally makes no sense. I mean if I set speed at 100 and drive 80, then it will of course try to accelerate. But giving the overall circumstances, it doesn't really make sense."

"It reacts to what it sees in front - just the car in front so to speak. It doesn't see what happens ahead. […] It is not that intelligent."

The overall findings regarding the System Performance lead to the conclusion that ADAS performance affects the driver's acceptance and willingness to use the systems. Inconsistent system performance causes the drivers to distrust the system's capabilities and take over the driving task themselves. However, looking into the previously discussed findings, it becomes clear that although the system performance and the context are closely linked, there are other, more individual factors that affect the user's engagement with the systems.

4. Discussion and research implications

This section discusses the design implications and possibilities for future research regarding ADAS development. Additionally, the main benefits of ND studies and the method used are presented together with the limitations of the study design.

4.1. The importance of the driving context

The aim of this paper was to pursue an understanding of how the driving context affects the use of ADAS. As made clear by the findings, the driving context affects both driver behavior and system performance, making the relation between the driver and the system flexible and unstable.

However, the quantitative data did not show a substantial impact of poor weather conditions on driving behavior, nor significant deviation during the seasonal change. Drivers usually freely use the system in the rain, differentiating only heavy rain, as system developers suggest it. During the measuring period, the conditions in the area did not get extreme very often. Bad visibility or snow covering the roads presumably does not happen often enough to show an effect on the monthly average. Therefore, it important to mention that even though measured data did not show a substantial impact of weather conditions on the studied vehicle pool, the situation could become significantly more critical in cases of ADAS evaluation across different markets. Other geographical areas with more extreme weather conditions might show a stronger impact of weather conditions on the ADAS use level.

On the contrary, the traffic conditions seem to remain the most critical part of the driving context. PA of the evaluated release was designed to be used in various traffic situations. Despite this fact, not all drivers are able to recognize this possibility. The results of this study showed that mainly drivers from the "High-level usage" group have reasonable confidence regarding the system and are curious enough to try PA in congested traffic situations. On the contrary, the drivers from the "Low-level usage" group are usually reluctant to experiment with the system in new contexts. They typically use the system in safe situations, ignoring newly designed and introduced benefits of the PA function.

Regarding the road conditions, the situation is undetermined. On the one hand, the high amount of roundabouts and other means for speed regulation helps to maintain a safe environment in residential areas. On the other hand, the limitations of PA are not allowed the system to perform stably with these types of speed regulations. The necessity to change lanes often, brake, and deal with crossroads makes the PA system less reliable in the eyes of drivers. They want the system to become smarter than before so that it can foresee the traffic lights, deal with intersections and lane changes, and understand speed limits. The road conditions, however, are difficult to change. Therefore, the adaptation of the functions to the road context becomes an extra challenge for the product developers.

Nevertheless, the findings of this paper are in line with Carta et al. (2011) and Angelini et al. (2018), whose results reporting that the contextual information supporting every event of the driving activity is an essential factor for a comprehensive ADAS evaluation. However, unlike the findings of Zhai et al. (2018), that identified the weather conditions and time of day as contextual factors of high impact on the driver behavior - this study showed that the road and traffic conditions have a larger impact on the drivers using ADAS compared to the weather and time of day. This contradiction could be explained by the differences in the context parameters included in the evaluation. The authors agree with Zhai et al. (2018) that the driving context highly depends on the assessed objectives. The driving context needs to be defined accordingly for every studied objective. According to Fridman et al. (2019), even a single underestimated variable can alter the results and shift the understanding of the context interrelation with the driver behavior. Although, according to authors understanding, studies such as Ahlström et al. (2018) and Ahmed and Ghasemzadeh (2018) are important to emphasize the effect of the stand-alone contextual factor on driver behavior; the driving context must be considered with the full spectrum of its complexity. Otherwise, it becomes difficult to transfer knowledge regarding the interrelating contextual factors and the range of their effect on driver behavior to the developers.

4.2. Method discussion

As the results show, combining quantitative and qualitative methods benefits the evaluation of the drivers' reactions to the changing system performance, due to the context as an influencing factor. Most of the limitations of quantitative data can be covered by possibilities of qualitative data and vice versa. However, a simple summarization of the results does not always lead to the achievement of a comprehensive understanding of the investigated phenomena. The data is usually different in nature and structure because the qualitative and quantitative studies are designed with a different focus, investigating various aspects of the same problem. In practice, the results are often not synchronized, incompatible, and difficult to use. Therefore, the sequential use of both methods allows building on the in-depth qualitative investigation of a specific issue of interest, using the insights of quantitative study. The issue of interest can be chosen after the results from the quantitative evaluation are obtained. Moreover, the choice of participants and the design of the questionnaire for qualitative study can be made according to the set objectives and based on the quantitative data analysis. Such an approach contributes to the high compatibility of the results between studies and allows the optimization of the data flow and resources for data utilization. Furthermore, the sequential mixed-method approach helps to cross-validate the results of both studies. This helps to evaluate the completeness of the datasets of both studies, by reflecting over the missing knowledge in the overall assessment.

Despite the great potential of ND studies for evaluation of ADAS and valuable results that can be achieved, three main limitations in the study design were detected.

One of the most significant limitations of the study is the difficulty of driver identification in the vehicle. Although the ownership of every vehicle in the ND study was matched to a specific driver, in some cases the vehicle was shared among the participant's family members. The absence of a driver recognition unit on board can lead to a problem, where the user behavior of another driver can potentially bias the results. It can specifically happen in cases where two drivers that share the vehicle have completely different use patterns regarding the evaluated system. In this study, it was not aimed to record the "clear" use patterns for each and every driver that can be used for modelling of user behavior and designing a communication to the driver. However, for cases when detecting a "clear" driver behavior is in focus due to the need for personalized communication to the driver, the problem of driver recognition needs to be solved.

The second limitation is the previous user experience regarding ADAS usage that was not considered during this ND study. Drivers with different levels of prior experience were participating in the study. Since our investigation was focused on the usage of ADAS, we wanted to maximize the conformance to the real situation on the market. However, the questions about the learning process were covered during the qualitative study. The results showed that the way drivers have introduced with the system (e.g., supervised test drive, learning by doing, etc.) affects the later use of the ADAS. Thus, if one wants to include the learnability assessment of the system in the quantitative study, the sample for the ND study needs to be narrowed to only inexperienced drivers. Moreover, the WICE-system needs to be installed at the moment of the distribution of vehicles to support quantitative data collection from day one, enabling a longitudinal study which can investigate the learning behavior over a period of time.

The third limitation is connected to the quality of the driving context description through sensors data. The detailed description of the driving context through vehicle sensors data is still not fully determined and needs to be developed continuously. For example, the congestion in oncoming-traffic was not considered during this study. However, as seen from the interviews, this might lead to the decision of the driver to not use the system, due to the higher possibilities of eventual obstacles from the oncoming lane. This finding shows that the triangulation of the quantitative and qualitative results gives real opportunities to identify hidden variables in the established data set.

Nevertheless, the means to override those limitations need to be investigated. This would enable a more in-depth analysis of the effects of the driving context to be performed and to obtain even more reliable results in future research.

4.3. Research implications and future work

The broad implication of the presented results is that the driving context affects usage through system performance, since the design limitations of the system performance affect how the driver perceives the system. The findings show that there is threefold interrelation that includes the driver, system, and context. To successfully design and develop ADAS, this interrelation needs to be considered. On one hand, the system has to function in a different driving context, on the other hand, it should meet the individual needs of drivers that use the system.

As previous studies have shown (Lindgren et al., 2008; Wang et al., 2016; Gonçalves and Quaresma, 2015), the driving context can differ significantly among the different geographical markets. Thus, ADAS designed for roads in Europe may not necessarily be optimal in other markets. For example, if we compare the Chinese and EU driving context, a number of differences can be identified. The amount and variety of road participants are much higher in China. The cultural differences and low safety barriers make traffic environment more complicated in China, leading to the different drivers' needs associated with ADAS usage (Wang et al., 2016). Further, the road infrastructure and weather conditions can be different between two geographical markets. For these range of differences, the system needs to be respectively adjusted to be able to meet the specific conditions of the driving context. For example, on the Chinese market the system should be more sensitive to the various types of road participants, including cyclists, motorcyclists, and pedestrians. Also, the system should be able to handle different queuing behavior, meaning smaller distances between vehicles, due to extremely dense traffic situations. The authors suggest that the driving context for different regions needs to be investigated prior to the system design and development. This information is required to develop ADAS systems that consider the critical differences between different markets. ND data can be extremely helpful for identifying and analyzing those differences.

Moreover, differences identified in driving behavior in the same geographical area indicate that there are also factors at the individual level involved. The findings of this study show that driver behavior is very diverse and influenced by system performance, driving context and human-related factors. Modification of the functions on a physical level to fit the different needs of the drivers is not feasible under such circumstances. A possible solution could be a personal-tailored assistance on the usage of the ADAS for the drivers. Different communication strategies can be introduced, e.g., satisfactory driving conditions for the system usage can be detected through the system and communicated to the drivers. This could facilitate an opportunity to try the ADAS in a suited context, which could lead to higher acceptance. Therefore, measuring real-time data for driver and system behavior in various driving contexts and comparing this to the historical data for the same driver can potentially enable personalized communication with the driver. In general, this communication could facilitate the interaction with the system, support system usage, or explain system deactivations in various driving conditions, gradually bringing the understanding of the system between drivers to a similar usage grade. Studies similar to the one presented in this paper help to collect historical data and analyze the driver needs for additional support. A combination of quantitative and qualitative approaches can significantly improve the understanding of the developers regarding the personalized solutions that can be introduced.

5. Conclusion

This study shows that, on one side, the driving context affects ADAS usage through system performance, showing that the limitations of the ADAS design affect the driver's trust and willingness to use the systems over the long term. On the other side, momentary decisions by the driver about activation/deactivation of the ADAS are directly influenced by the driving conditions at the time the decision is made. Thus, the findings clearly indicate the threefold interrelation that includes driver behavior, system performance, and driving context. In order to facilitate driver engagement with ADAS, developers need to take this interrelation into account and consider driving context in the design and development of the system. The system has to function in various driving contexts, and it should meet the individual needs of drivers who use the system.

Furthermore, the prevalence of the context parameters needs to be further studied. The authors suggest conducting more studies, presumably with the consideration of different markets, to validate findings and rank the contextual factors. Additionally, vehicle sensors and means of driving context assessment need to be continuously improved to be able to provide a comprehensive driving context understanding.

Future studies are also required to identify human-related aspects affecting the use of ADAS, i.e. drivers perception and understanding of the system. The next-generation systems must be crafted with regard to all affecting factors, to ensure that the needs of the users are met.

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