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Design and implementation of driver coach application for pilot assist: A first validation study

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ABSTRACT

This article discusses the importance of driver understanding and trust in Advanced Driver-Assistance Systems (ADAS) and proposes a framework for a personalized driver coaching system called Driver Coach, focusing on the Volvo Pilot Assist (PA) function. Despite the widespread adoption of ADAS, research indicates that many drivers have limited comprehension of ADAS functionality and limitations. Moreover, feedback-related factors play a crucial role in determining drivers' proper use of ADAS. The article emphasizes the need for appropriate, continual feedback to enhance driver interaction with ADAS. Traditional methods, such as user manuals or supervised test drives, have limitations in effectively conveying critical information and facilitating driver adaptation. To address these challenges, the proposed Driver Coach app provides personalized, real-time recommendations to drivers based on their individual needs and understanding of both the system and driving context. The app was tested in a field trial involving 17 drivers over a four-month period, and the results regarding the logic design verification and the impact of the Driver Coach app on PA usage are presented. The findings highlight the potential of personalized, context-aware coaching systems to improve driver understanding and usage of ADAS.

Introduction

In the last decade, Advanced Driver-Assistance Systems (ADAS) have become a new area of advancement in the automotive sector. With the help of technology, such as sensors, radar, and cameras, various ADAS are designed to serve different purposes: to detect nearby obstacles and assist in avoiding collisions, provide satellite navigation and traffic warnings, assist in steering or maintaining speed, or detect driver errors and respond accordingly, or provide other features (Galvani, 2019). Due to established road safety advantages, as documented by Masello et al. (2022), numerous automotive Original Equipment Manufacturers (OEMs) have begun incorporating these systems as standard features in their newly launched vehicles.

Despite the rapid development of automated technology, some ADAS remain semiautomated, meaning that the driver should supervise the ADAS performance and, if needed, take control of the vehicle at any time. Thus, safe use of ADAS requires the driver to understand ADAS functionality and limitations. Nonetheless, extensive research shows that many drivers do not fully understand how ADAS functionalities work or their limitations (McDonald et al., 2018). According to Llaneras (2006), drivers often mistakenly believe that ADAS can handle driving situations even if the system activation preconditions are not fulfilled or have reached their limits. A study by Jenness et al. (2008) also reveals that approximately 80% of respondents were unaware that ADAS could not detect all stationary obstacles, pedestrians, or pets. Aziz et al. (2013) show that participants mistakenly believed that the ADAS function could work at any speed, forming another misconception regarding ADAS capabilities. Most drivers are unaware of the design limitations when their first interaction(s) with ADAS occurs (Larsson, 2012; Victor et al., 2018), trying the system in actual driving conditions. In this situation, even a cautious driver may mistakenly over-trust the automation or, vice versa, be reluctant to use it if the fundamental limits of ADAS performance are unclear (Itoh, 2010). Both cases would harm the driver's trust and acceptance of the technology (Itoh, 2012; Kazi et al., 2007).

In addition to poor comprehension of ADAS limitations, feedback-related factors also determine whether or not drivers will use the

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system as intended (Jamson et al., 2013). According to Norman (2007), the problem of automation is not actually in how well the system can handle unexpected events but rather inappropriate feedback that results in inadequate interaction. Thus, the way ADAS interacts with the driver is crucial, especially if the system is semi-automated. In his paper, Norman underlined the importance of providing appropriate, continual feedback instead of communicating the simple changes of status, such as system active/not active. The lack of explanations from the system side keeps the driver "out of the loop" regarding the technical processes and reasoning behind poor system performance. Such insufficient feedback increases drivers' mental workload and produces stress, since the driver needs to ascertain on his own if something is wrong.

For automotive OEMs, it is vital to develop driver trust and so acquire their efficient use of ADAS systems. Nevertheless, as indicated by the findings of the study conducted by Boelhouwer et al. (2020), nearly a quarter of drivers receive no information regarding the ADAS features integrated into the vehicles they purchase. Providing a detailed manual is not the best solution either since people prefer to try the system as they drive (Larsson, 2012; Forster et al., 2019), creating their own impression of the system, only referring to the manual if a problem arises. This "learning by doing" results in a different outcome, depending on an individual's ability to comprehend the system (Novakazi et al., 2020). A test-drive with professional supervision, as another OEM solution, also has its limitations. The number of systems in the car and the amount of information received during the short test-drive time have shown to prevent an appropriate driver adaptation to the new environment. Recent results of the ADAS follow-up systems show a great diversity in how drivers use and understand the ADAS (van Huysduynen et al., 2018; Orlovska et al., 2020; Novakazi et al., 2020), from no use and poor understanding to high and efficient use of the systems, and to overreliance and misuse of the systems. Thus, OEMs need better ways to convey critical information regarding ADAS capabilities and limitations to the driver (McDonald et al., 2018). Different users require different learning strategies due to the speed at which people comprehend the information. Drivers' previous experience, needs, the general attitude toward automation, and even current state affect drivers' behavior (Hasenjäger et al., 2019). For example, Trübswetter and Bengler (2013) shows that the risk of not understanding the system in a time-efficient manner is higher for older people than other user groups, which outweighs the benefits of ADAS support for them and results in lower use of ADAS. Therefore, the standardized learning process will not always be adequate and effective for all users (Beggiato and Krems, 2013). Thus, automotive OEMs need a personalized approach to the learning process based on the driver's individual needs and current understanding of the system (Orlovska et al., 2020; Hasenjäger et al., 2019).

Furthermore, personalized feedback needs to consider the dynamic driving context (the combination of traffic, road, and weather conditions) that significantly affects ADAS performance. This means personalized feedback has to be organized in real-time (Orlovska et al., 2020), supporting drivers' desired way of "learning as they go." Such an approach will allow personalized support of different users, illustrating, in real-time situations, how the ADAS can be used and where it reaches its limits.

This article proposes a detailed framework design for the Driver Coach system for one of the ADAS functions, namely Volvo Pilot Assist (PA). Driver Coach app for PA is a personalized context-aware driver coaching that aims to teach users about PA limitations and promote a broader PA use strategy. As a next step, we performed the fully functioning PA Coach app based on the framework design presented in this paper. This Driver Coach app establishes personalized, context-aware, one-way communication with the driver, providing straightforward recommendations in real-time on how the particular driver could improve the PA use strategy. The Driver Coach app was tested in 17 drivers for four months in a field trial where participants used it in their daily driving. The study results on the logic design verification and the effect of the Driver Coach app on PA use are consequently presented in this paper.

The rest of the article is structured as follows. First, we present a short overview of related research in Section 2. Section 3 presents a framework for real-time Driver Coach support. Then, section 4 provides details on the logic design, back-end solution, and front-end design for the Driver Coach app for PA. Section 5 explains the study method for Driver Coach app tests in real driving environments. Section 6 presents our main findings, connected to the Driver Coach app tests in real driving environments. Finally, in Section 7, we discuss the main limitations of this study and reflect on further improvements.

Overview of related work

Today, service-based solutions are employed in many areas, such as e-health, smart homes and mobility, education, and other domains, providing context-aware support to app users (e.g., Alférez et al., 2014; Guermah et al., 2014; Wu et al., 2008; Han et al., 2013). Several frameworks are also presented within the automotive domain (e.g., Gilman et al., 2015; Brouwer et al., 2015; Syed et al., 2009), focusing on driving safety improvement, fuel-efficient and eco-driving, contributing to better environmental indicators. In contrast, studies focused on helping drivers deal with the newly introduced in-vehicle systems, functions, or a new car's capabilities are scattered or just soliciting for new policies (e.g., Pearl, 2018). However, driving itself is a complex task. The driver has to undertake multiple decisions simultaneously. These decisions could relate to vehicle control, adjusting the speed or trajectory, making strategic decisions, and dealing with hazardous situations. At the same time, the new adaptive or automated functions pop up with remarkable speed, increasing the driver workload with the new tasks related to the comprehension of these new systems (Paxion et al., 2014). Thus, a study focused on drivers' effortless education of in-vehicle functionalities is timely and essential.

The overall analysis of research approaches focused on driver coaching helped identify several weaknesses related to the coaching design:

i. Personalization of support is often not considered in study design. As a result, users receive standardized support based on, for example, performing the operation at the current moment.
ii. Often, real-time support is not part of the design, meaning that the communication with the driver is not implied in real-time but afterward, which allows the driver to reflect on the identified issue but not immediately act upon it.
iii. The study design is often based on existing datasets where researchers could not modify or extend the number of data points to better capture the driving event or its context.
iv. Self-learning or adaptive behavior of coaching systems is often not considered. The user receives the same types of notifications (and often at the same frequency) without considering the driver's reaction to this event.

Thus, although many applications for ADAS personalization have been proposed in the literature, only a few were implemented and tested in practice (Lv et al., 2018; Hasenjäger et al., 2019). This paper presents the design of a fully functioning Driver Coach application based on the personalized approach, which was tested on 17 drivers in a natural driving environment. Our design is unique in combining the following five essential characteristics:

1. Performance-based drivers' categorization regarding the use of the PA.
2. Real-time driving event and driving context recognition.
3. Several driver support strategies are implemented based on driver behavior analysis in various contexts.
4. Personalized communication based on the driver's use strategy with PA.

5. Meta-analysis of the driver response to the implemented strategy and adjustment of the communication strategy when needed.

Our framework's design provides a real-time support strategy that coaches drivers and is self-adaptive based on driver behavior and driving context changes. The detailed framework design is presented in the following chapter.

A framework for real-time driver Coach support

Framework design is a generalization of the approach presented by Orlovska et al. (2020) and the direct continuation of this work, with a focus on detailed design of modules and issues related to the practical implementation of this design. The framework consists of four levels, namely Input level, Reasoning level, Output level, and Meta-reasoning level. Fig. 1 presents a high-level schematic design for Driver Coach, focusing on what data needs to be collected and how it needs to be processed to provide an adaptive real-time driver coaching system.

On the *Input level*, the framework describes what data need to be considered to identify and classify the driver, understand the in-vehicle system performance, and describe the required context to provide coaching that takes account of a driver's previous experience and current use strategy for the system. Thus, the resource repository could contain historical data on driver behavior. This data can be used for driver categorization and the modeling of a personalized coaching approach. Furthermore, metrics that indicate driver performance, style, preferences, and/or non-driving-related activities could be used to optimize the design of the driver coaching strategy. It is important to note that most user-related metrics are classified as sensitive data. Therefore, the GDPR rules for data collection and utilization need to be considered, and data collection should be done with the driver's consent. Although collecting personal data is challenging, it helps uncover even more human-related aspects. For example, detecting driver distraction, drowsiness, excitation, and other human states allow for deciding the best time for interaction with the driver. Furthermore, the data points for a coaching event recognition and analysis have to be chosen considering the system performance, its context, and the performance of systems related to that being coached, if any.

On the *Reasoning level*, modeling the correct strategy for the user occurs. The coaching design should be connected to its purposes. Communication strategies can be of different types, ranging from promoting a feature in a specific context to preventing unwanted use of the function, from proposing an optimal solution to explaining functionality to new users or other types of support. Thus, the coaching strategy would depend on driver behavior, system performance, and the interaction context. The driver-related data are used to identify the driver and classify their behavior. The parameters for driver classification need to be chosen based on the study objectives. If we want, for example, to promote a specific system, we should consider driver behavior in all possible contexts with this system to determine where driver behavior can be improved. But if the objective is to eliminate a particular driver's behavior when using a system, it would be reasonable to limit driver

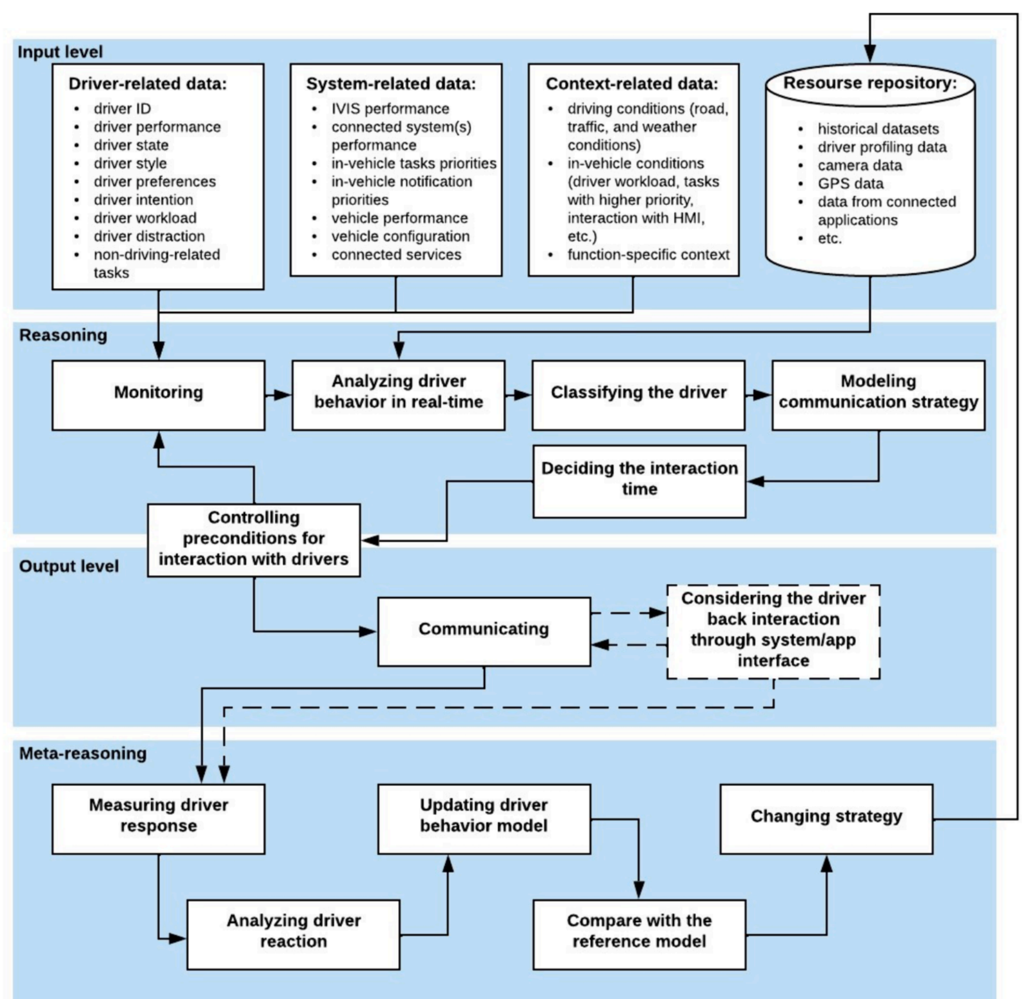

Fig. 1. Framework design of the Driver Coaching process.

behavior classification to the behavior in this undesirable context. Thus, the driver's behavior assessment could differ for different tasks, but it remains one of the key characteristics that classify the driver. Context-related and systemperformance data need to be processed in real-time to identify the event and check all the preconditions before communicating with the driver. The interaction time and the coaching frequency should be designed for each user separately, depending on the driver's individual schedule, behavior and/or reaction to coaching.

On the *Output level*, the communication takes place. There are many ways to output coaching support to the driver: message on the screen, graphics, voice, alarm signal, and others, including a combination of the above. A selected technique(s) has to be implemented with safety constraints in mind. Driver distraction, due to coaching, should be minimal so that the driver should be able to focus on the primary driving tasks. Another thing that needs to be considered is the overall hierarchy of in-vehicle events and notification priorities. Suppose another in-vehicle notification co-occurs with the message from the Driver Coach; in that case, the notifications must be placed in the queue and communicated based on their priorities. The overall understanding of task priority becomes even more critical in the case of a fullyintegrated app.

Finally, on the *Meta-reasoning level*, we need to understand the effect of coaching on the driver, processing and analyzing the driver's response to the communication event. When driver reaction is understood, the Driver Coach should reflect on the eventual change in driver behavior and adjust, if needed, the coaching strategy applied to the specific driver. A selflearning coaching support should be adaptive. The Driver Coach should learn from the driver's responses, monitor the change in driver's use strategies, and decide how soon this driver reaches the next level or what communication strategy is best for the moment. The consistency and speed of driver behavior transformation and the extent of change could be key parameters when reassessing the coaching strategy.

The Driver Coach Framework, presented in this chapter, describes a general process of coaching design. However, in practice, different activities within this framework could meet various restrictions from automotive OEMs. These restrictions are primarily connected to data availability, GDPR restrictions, real-time data processing solutions, and back-end realization for these types of studies. The next chapter presents a detailed design of the Volvo PA Coach app as an example of the practical implementation of the proposed framework. Specific limitations met will be further described, together with the way they were specifically addressed in this case study design.

Driver Coach app for PA: The application design

In this paper, we proposed and fully developed a personalized context-aware Driver Coach application to support the learning process in real-time of one of the ADAS functions, namely Volvo Pilot Assist (PA). The logic design of Driver Coach app for PA was earlier presented in Orlovska et al. (2021) as a theoretical concept for real-time personalized support that conveys the system's capability to a driver and helps create more compelling use strategies in various traffic conditions. This paper presents a final version of the implemented design that considers the OEM's capacity for data collection, back-end architecture, output channels, the front-end design, and verified logic of the whole coaching concept.

Driver Coach app for PA: The logic design

Volvo PA is one of the advanced ADAS features that uses vehicle cameras and radar systems to provide both longitudinal and lateral vehicle control. Using longitudinal control of the vehicle, the feature automatically adjusts vehicle speed and following distance by considering the time interval to a moving object in front and the driver's preselected speed. Lateral control of the vehicle provides steering assistance or the ability to keep the car within the road lane (VOLVO Cars, 2022). While PA functionality undoubtedly offers excellent benefits to a driver, the current PA version is not fully automated, requiring the driver to understand PA limitations, supervise its performance, and quickly take over the control of the car whenever the PA performance quality decreases. The current PA version cannot provide its assistance in all driving conditions. PA's main limitations are related to the following driving conditions: slippery roads, poor visibility, high curvature of the roads, roads with no clear markings, high precipitation, and highway ramps (VOLVO Cars, 2022). Accordingly, the Driver Coach app design is focused on teaching the PA limitations to the users and promoting a more diversified PA use strategy, leading to a better driving experience with the PA. A better driving experience in the context of this paper will be achieved if a driver: (1) starts making fewer mistakes while using PA, (2) learns through the warning design support of the Driver Coach in limiting contexts, and (3) starts using the system more efficiently, following the Driver Coach recommendation's design.

For the convenience of the implementation and verification process, the Driver Coach framework, presented in Fig. 1, was modified into the modular design, shown in Fig. 2. The main advantage of modular design is the possibility of dissecting a complex system into smaller parts, facilitating the design, development, and testing of each module independently from other modules (Baldwin et al., 2000).

Module A: Identify and classify the driver

In the initial module A, the app should be able to identify and classify drivers by connecting driver identifiers and their historical data to the model. The Volvo design doesn't imply direct driver identification models yet. Therefore, we assigned our users to their cars through Vehicle Identification Numbers and set the requirement to the test pool that the drivers in our study have to be sole users of their vehicles or only share their cars on rare occasions. We temporary accepted this limitation. However, if driver identification becomes possible in the future, the data points resulting from the driver identification process can be added to the current logic as soon as this happens.

Furthermore, historical data was collected to understand the prior PA use context and use strategy for each driver. A broad diversity in drivers' PA use strategy led us to conclude that different drivers need different coaching strategies, depending on their previous experience, developed skills, perceived usefulness of the PA feature, etc. In this

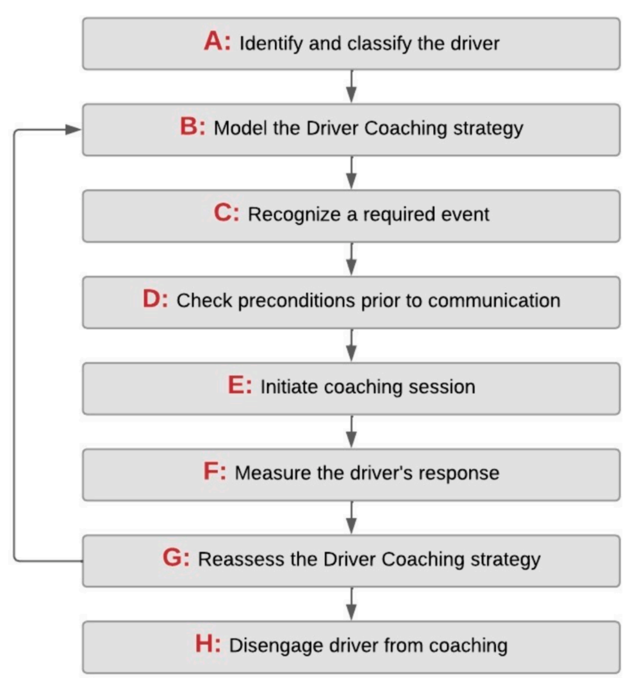

Fig. 2. Driver Coach logic design modules for Pilot Assist.

particular case, the use frequency of PA and traffic conditions were the main parameters for driver categorization, allowing to classify a driver and model the best coaching strategy for that particular driver. For the traffic context, we distinguished two different traffic conditions, namely sparse and dense traffic. The reason is that we want drivers to understand that PA can be used in more diverse and demanding situations. In sparse traffic, PA's ability to provide longitudinal control is almost not used since there is no need for braking/acceleration. In total, nine driver categories were derived. The driver categorization table can be found in the Appendix 1 (Table A1).

According to our vision, the performance of drivers from categories 1–6 can be improved for one or more parameters, while drivers from categories 7–9 are considered knowledgeable users since they use and trust PA in dense traffic. Dense traffic is more demanding and requires trust in PA since PA needs to perform constant braking and accelerations depending on traffic in front. Thus, if drivers can use and trust PA in dense traffic they can obviously use it in less demanding sparse traffic when there is no need to brake and accelerate. Therefore, drivers with category 9 are considered more advanced compared to drivers from category 5. Their low use or no use of PA in sparse traffic could indicate the low benefit of PA for drivers. Therefore, for drivers from categories 7–9, we do not apply stimulation strategies. They only receive warning notifications when using PA in unstable conditions.

Module B: Model the driver coaching strategy

In module B, we assign drivers from different categories a specific communication strategy. Since the PA Coach app aims to improve the effectiveness of PA use strategy, help drivers learn PA capabilities and limitations, and identify the appropriate/inappropriate context for PA activations, three types of coaching strategy were designed:

1. Stimulation strategy that focuses on improving drivers' engagement with PA in different traffic conditions: (R1) recommends PA usage in sparse traffic; and (R2) recommends PA usage in dense traffic.
2. Warning strategy informs drivers about the critical conditions for the PA performance, such as: (W1) using PA in low-speed areas; (W2) using PA during poor visibility; (W3) high precipitation; (W4) slippery road conditions; and (M1) using the PA when exceeding the speed limit by more than 20 km/h.
3. Explanation strategy provides inexperienced drivers with additional information on stimulating and warning events, explaining how to navigate PA and control PA status (E).

The detailed descriptions used for the design of different driver coaching strategies are presented in Table 1.

The choice of coaching strategy for each driver category is shown in Fig. 3. Module B, however, does not consider the frequency of communication and the pace for driving category improvement; these are decided later in the design and based on individual changes in performance and reaction to coaching support. More details on that can be found in Module G.

As Fig. 3 shows, our logic design also implies a delay in the app performance support for two minutes from the start of driving. This time is needed to synchronize the external data acquisition system with the cloud server, and establish a good connection between the car, cloud server, and the application.

Module C: Recognize a required event

In Module C, the Driving event needs to be identified in real driving time to support drivers in real-time. We have designed seven events when driver coaching strategies can improve driver behavior and understanding of PA use context. Table 2 presents the driving event descriptions, and Fig. 4 shows the conditions we applied to identify each event.

As shown in Fig. 4, the design for identification of the events F(M1) and F(W1-4) implies only the use of one critical parameter for PA

Table 1
PA driver coaching strategies.

Strategy	Code	Classification	Name	Description
Stimulation strategies	R1	recommendation	Promotion of PA in sparse traffic	Stimulation of PA usage in sparse traffic conditions if no warning scenario is in place. Thus, before recommending the use of PA, we need to ensure that no warning scenarios (W1, W2, W3, W4, M1) are present.
	R2	recommendation	Promotion of PA in dense traffic	Stimulation of PA usage in dense traffic conditions if no warning scenario is in place. Thus, before recommending the use of PA, we need to ensure that no warning scenarios (W1, W2, W3, W4, M1) are present.
Warning strategies	W1	warning	Use of PA at lowspeed limit	When the driver uses PA while speed limit is equal or below 30 km/h, which indicates a residential area, construction works and other critical conditions.
	W2	warning	Use of PA in low visibility	Visibility is considered to be low if the fog light status is ON.
	W3	warning	Use of PA in high precipitation	Precipitation (rain/snow) is high and at the limits at which PA performance could be reliable.
	W4	warning	Use of PA on slippery roads	Possibility of slippery road conditions. The temperature is in the range from −2°C to 2 °C.
	M1	mistake	Over-speeding while driving PA	Situations when driver uses PA and is more than 20 km/h above the speed limit.
Explanation strategies	E	explanation	Explanation of driving context and/or PA performance change	An additional message aims to explain to new users PA limitations (connected to W1, W2, W3, W4, M1), explain the benefits of using PA in various traffic conditions (related to R1, R2), or explain how to navigate PA, take control over PA, and change its status.

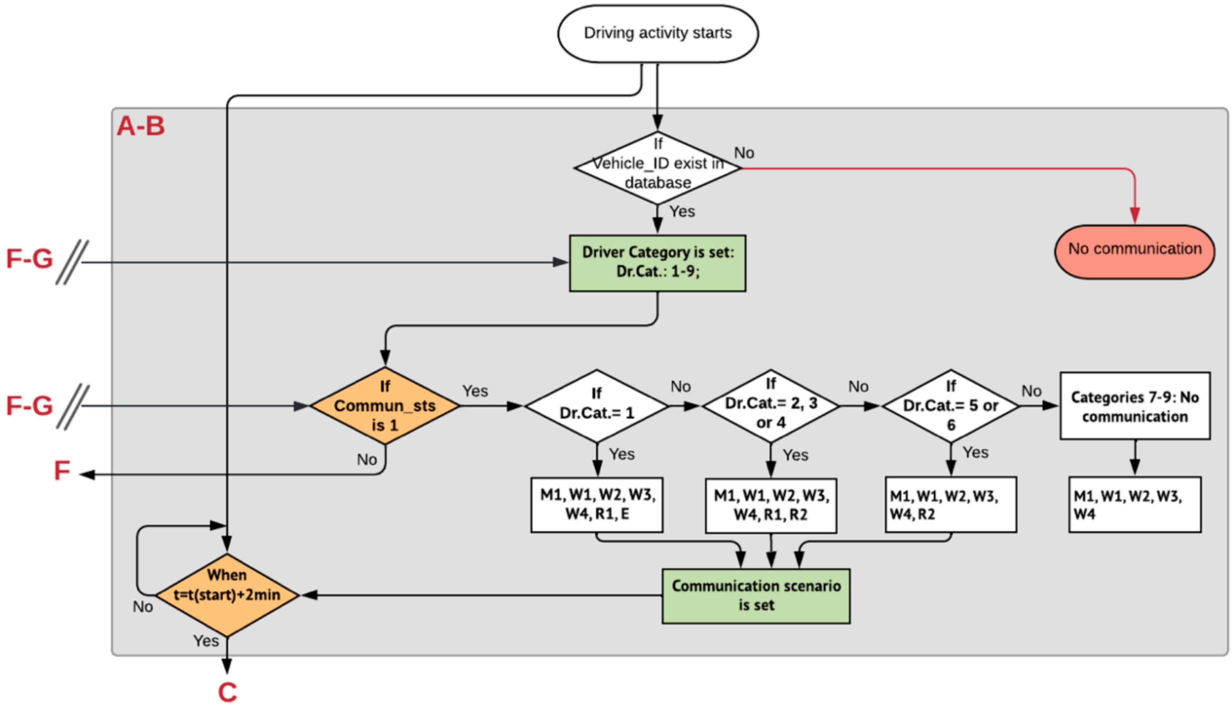

Fig. 3. Detailed design of PA Coach app: Modules A-B.

Table 2
Driving Event descriptions.

Event Name	Event Code	Explanation
Sparse traffic	F(R1)	Using PA in sparse traffic helps maintain chosen speed and keep the car in the same lane, leading to safer driving due to decreased active driving behavior, often overtaking, changing lanes, etc.
Dense traffic	F(R2)	Using PA in dense traffic saves a driver's energy in pressing the gas/brake pedal and keeping a safe distance to the vehicle in front. This behavior contributes to "driving in the flow," leading to more relaxed and safer driving.
Use of PA in low-speed area	F(W1)	Connected to PA limitations that say PA can have trouble recognizing small objects or pedestrians on the road.
Use of PA in low visibility	F(W2)	Connected to PA limitations that say PA performance could be unstable when visibility is low.
Use of PA in high precipitation	F(W3)	Connected to PA limitations that say PA performance could be unstable when precipitation is high.
Use of PA in slippery road conditions	F(W4)	Connected to PA limitations that say PA performance could be unstable in slippery road conditions.
Speeding with PA	F(M1)	Connected to safety issues: speeding above the limit by 20 km/h is classified as dangerous behavior. Applying this behavior to automation also cannot guarantee driver safety.

performance. In contrast, the identification process of dense F(R1) and sparse F(R2) traffic conditions is more complex. First, based on *driving speed S(d)* and *speed limit sign information S(L)*, we identify traffic conditions in the current moment of driving. Then, we verify this condition with the *driving time to the vehicle in front R(d)*, calculated based on the driving speed and distance to the car in front. Finally, we set a *timer (t)* on the event duration to eliminate non-lasting conditions when a driver decreases speed due to pedestrians crossing the road, traffic lights, or other short-time conditions that are not connected to the traffic.

Module D: Check preconditions prior to communication

Module D is designed to support the stimulation strategy's events F (R1) and F(R2). Since we promote PA usage, we need to ensure PA would provide reliable performance in the proposed conditions. Moreover, we need to verify that the conditions creating the limitations for PA performance (W1-W4) are not in place. Therefore in this step, we check:

1. *Driving context* (road and weather conditions). We confirm that the lane markings are represented from both sides, the visibility is good, the precipitation is not too high (wiper speed is not high), and road conditions are not slippery.
2. *Driver intentions*. This study design only uses turn indicators to forecast driver intention to turn, change lanes, or override other vehicles. In the case of turn indicators status ON, PA promotion is postponed since PA will not be functioning during the maneuver, switching its mode from active to standby. Switching mode means that the build-in interface will change its color from green (fully functioning) to grey (standby mode or off mode). Therefore the promotion of PA activation in this situation would be confusing for a driver.
3. *The equipment response* (radar and cameras). If the radar system or cameras are not functioning or cannot deliver their signal due to mud cover or any other reason, the PA could not provide its functionality. In this case, the proposal of PA usage would also be irrelevant. Therefore the equipment response also needs to be verified.

Fig. 5 describes the designed logic and set thresholds for driving situation verification before recommending PA activation. If, before communication, all conditions are OK according to the designed logic, then the app outputs its recommendation message.

Module E: Initiate a coaching session

Module E is focused on the rules' design for communication with a driver. Thus, communication sessions with the driver are carried out, taking the event priority rule into account. The over-speeding mistake F

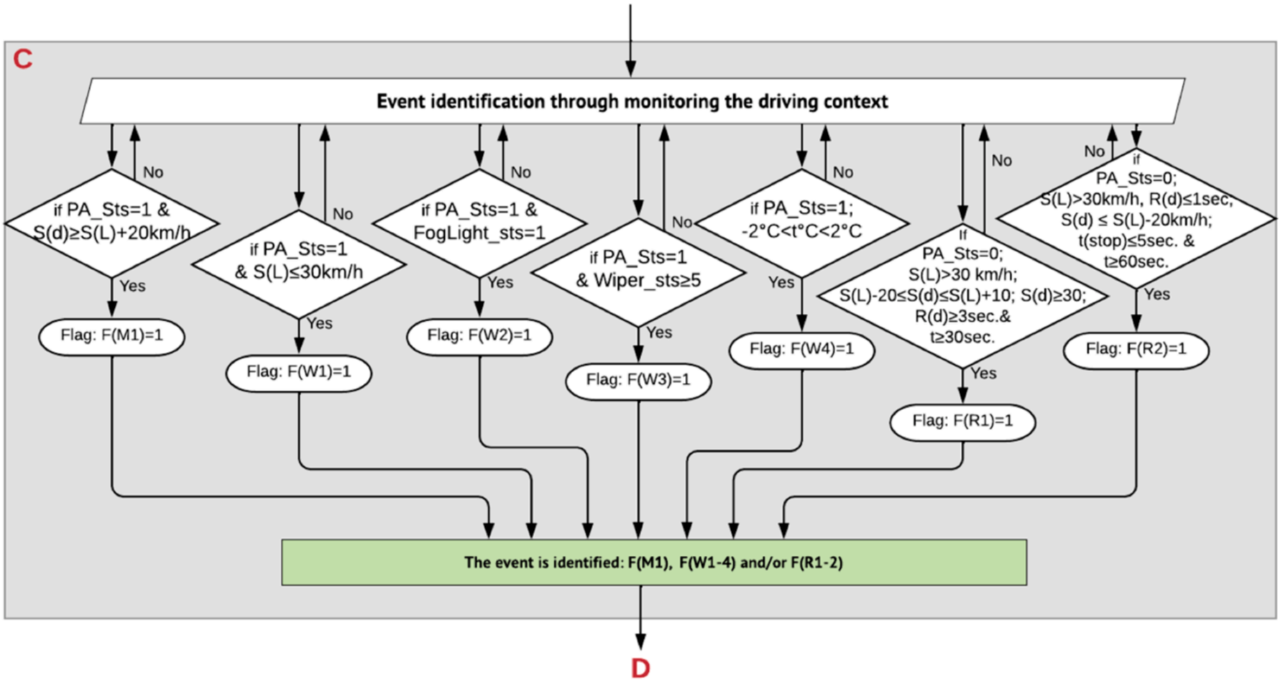

Fig. 4. Detailed design of PA Coach app: Module C.

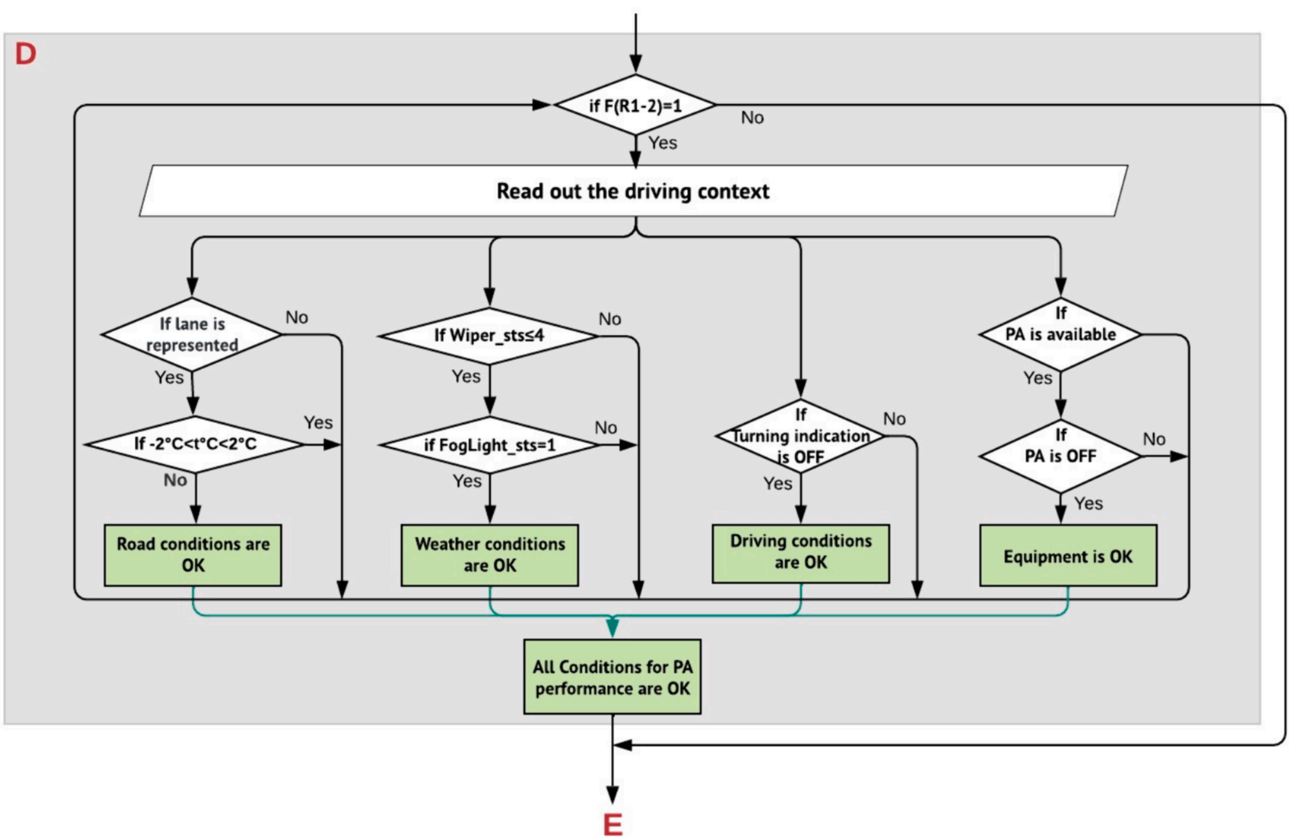

Fig. 5. Detailed design of PA Coach app: Module D.

(M1) has the highest priority since it has a direct connection to driver safety. Warning events F(W1-4) are next on the priority list. Recommendations F(R1) have the lowest priority, meaning that this event is only communicated when no warnings or mistakes are detected. All four warning events F(W1-4) within the group have the same priority and proceed with the rule “first come, first serve.” The same applies to two stimulation events, F(R1-2), which have equal importance and are processed independently from one another.

Furthermore, frequency rules within one driving activity are applied. For mistake M1, the frequency rule says that the message connected to event F(M1) has to be repeated in two minutes if the conditions for M1 persist (the driver neither decreases speed nor deactivates PA). For the complete driving activity, the app could communicate a maximum of two disconnected events F(M1), with the option to repeat the warning in two minutes if the driver does not react. The frequency rule within one driving activity for warning events F(W1-4) is set to a maximum of twice per driving activity with a minimum interval of 10 min. No repeats of warning messages are implied for the events F(W1-4) since the goal is not to make them act upon the notification but instead raise their attention to the road situation. Finally, the recommendations F(R1-2) are communicated with the frequency of a maximum of one message (for each event type) per driving activity. Fig. 6 shows the detailed design explaining communication priority and frequency for each event.

The design of the output messages is presented in the Appendix 1 (Table A2). These messages are voice messages that are recorded to enrich graphical changes on the app screen. Additionally, sound notification in the form of a beep is used to raise driver attention to the message that follows. A more detailed description of the front-end of the app design is presented in Section 4.3.

Explanations are designed only for recommendations R1 and R2, and will only be output to the drivers in Category 1 who have no recorded experience of PA. For warnings W1-4 and M1, short explanations are incorporated into the main message to explain PA limitations and teach drivers how to identify the critical context for PA performance.

Module F: Measure the driver's response

After the driver receives a notification, we should understand the driver's reaction. Since the automotive context has strict requirements about minimizing distraction from the main driving activity, we designed a one-sided application that does not provide direct driver feedback. Measuring driver behavior after a recommendation helps us realize whether the driver followed our suggestion or not. Thus, we need to understand the driver's reaction through his behavior change. As for the recommendations, we identified three driver reactions: (1) PA used in the conditions we proposed; (2) PA used in other conditions; and (3) PA is not used.

As for warnings F(W1-4), no specific reaction exists since we are not requesting particular actions from the driver but want to raise their attention to the driving situation and PA performance ability. We expect that the number of warnings should increase in the beginning, when drivers are exploring PA capabilities, and decrease with the length of time using the PA Coach app. This behavior would mean that the drivers understand systems limitations better and are able to recognize and avoid the critical context for PA performance.

As for event F(M1), we identified three driver reactions. Within the time interval of five seconds, we look at whether: (1) drivers reduce

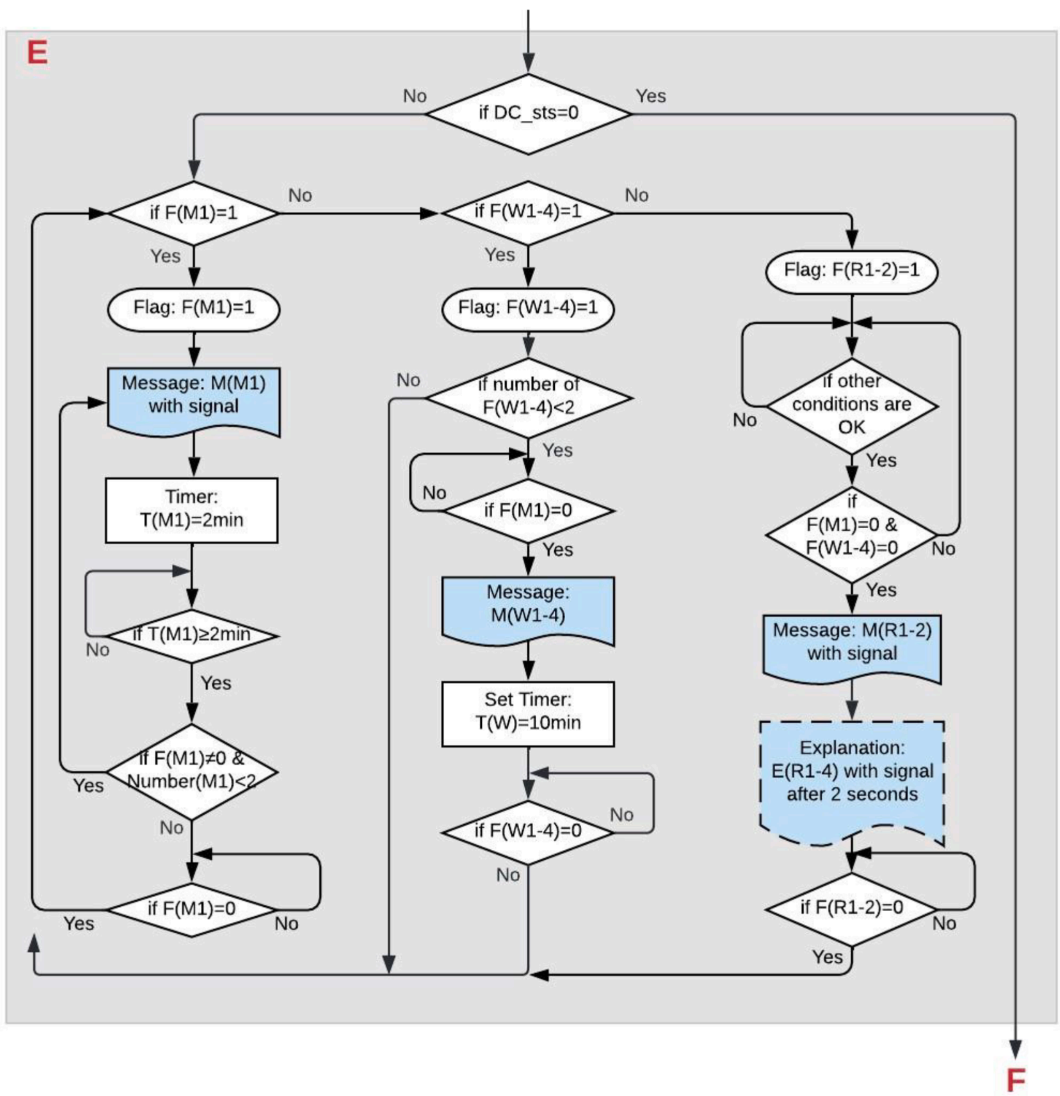

Fig. 6. Detailed design of PA Coach app: Module E.

speed, (2) deactivate PA switching to active steering, or (3) ignore our notification. These reactions are not part of the driver category update since the mistake, in this case, is not connected to how well the driver uses or understands the system but to the driver's safe driving behavior. In the long term, we expect a decrease in speeding notices while using PA with the increase of the application usage time, unless the driver's usual behavior includes speeding.

Module G: Reassess the driver coaching strategy

Understanding the driver's reaction to the recommended use of PA enables us to control the range and speed of driver behavior change. This helps reassess the driver coaching strategy and, if necessary, adjust it according to the user's needs. Our logic reconsiders the following aspects:

A: Communication frequency. If the mistakes and warnings we communicate all the time they happen, limiting only the maximum outputs within one driving activity, then the logic for the recommendations is different. Besides the limit on maximum notifications within one driving activity described in module F, our reasoning for PA promotion considers the frequency of using the car. Since the goal of driver coaching is to teach drivers to recognize the appropriate context for PA use, we want to guide drivers but not make them unconsciously follow our recommendations. Therefore, we introduced the *"Day-OFF"* concept.

Suppose the driver followed our recommendation (Driver reaction = 1 at least once during this driving activity). In that case, the complete driving activity gets status 1, which is followed with 2-Days-OFF. The 2-Days-OFF time is equivalent to 49 (48 + 1) hours. One extra hour is used to avoid catching a driver with our recommendations at the same time and place, during his morning commute, for example. But if the driver followed our recommendation in a context different to the one proposed (Driver reaction 2), then the complete driving activity gets status 1, followed with the 1-Day-OFF (24 + 1 h). The activation of PA implies a positive attitude from the driver, but the mismatch in context shows that the driver did not get the context correct. If the driver did not follow our recommendation (Driver reaction 3), the complete driving activity gets status 0, followed by the 2-Days-OFF. In this case, one of the possible reasons for non-compliance with the app's recommendation could be disagreement with the application's opinion about the appropriateness of the proposed context. Hence, a further pushing of the driver would be poorly perceived, and is something we want to avoid.

B: *Driver category.* The driver category updates are performed following the logic shown in Fig. 7.

Since the PA is an optional function with no strict requirements for how the driver uses it, the drivers' category upgrade plan follows the logic: a driver can upgrade his category but not downgrade it. A demonstrated ability to perform at a certain level means that the driver has developed the skills and understanding that we wanted them to acquire. If the driver later reduces the use of PA, this will mean that this is the driver's conscious decision. This logic complies with our goal, which is not to simply increase the use of Pilot Assist but to show its abilities and let the driver decide what use strategy fits best.

C: Communication strategy. Communication strategy is tied to the driver category. The update of the driver category leads to an automatic communication strategy's update. As a result, the driver receives a new scenario.

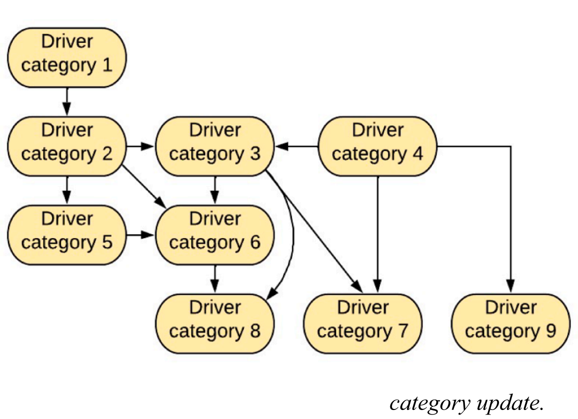

Fig. 7. Schematic design for driver category update.

Module H: Disengage the driver from coaching

Disengaging drivers from coaching means cancelling the recommendation strategy for drivers within categories 7–9. These drivers are advanced PA users who do not require any promotion or explanation strategy. They know how to use Pilot Assist in various contexts and therefore do not receive any recommendations from the app. However, they will continue to receive notifications regarding warnings or mistakes if they occur.

Driver Coach app for PA: The back-end process organization

The real-time driver-system communication is designed to keep the default PA interface, providing only an additional display for output of information from the Driver Coach application. Thus, the driver enables or disables the function through the vehicle interface's actuators as usual. The input from actuators and supportive sensors transforms into signals generated in CAN and Flex Ray busses of the car. Since the Volvo software platform does not support direct data transfer from the vehicles, the external wireless communication and data acquisition unit (WICE) was developed. The WICE serves as an intermediate solution to support the testing and validation stages in automotive development through efficient telematics technology and global coverage (Johanson, 2017). Overall, the system provides metrology services from connected vehicles, including collecting measurement data signals of various types (logs, signals, images, video, etc.).

The WICE system consists of two major parts: (i) Wireless Communication Unit (WCU) and (ii) Back-end server infrastructure. WCU is the hardware unit that supports communication interfaces for data logging and measuring, including telematics services. WCU hardware is installed in all test vehicles to enable required data collection and management from the vehicle fleet. Back-end server infrastructure includes the web-based front-end user interface, including data storage units and a database of *meta*-information.

The WICE portal implements the core functionality of the supported services, including fleet management of connected vehicles, tasks and data management, user management, and administration. The WICE portal is a complex software, providing server-side functionality for vehicle testing, verification, and development. WICE users interact with the system through the web front-end that gives users access to the WICE application services and data for retrospective data analysis. The WCU hardware unit contains monitoring and diagnostics modules and enables in-vehicle data capture, including GPS positioning and vehicle status information. The state of the WICE system is kept in the WICE database. The measurement data logged from vehicles is stored in the WICE file store, large volume storage based on the data lake concept.

Although WICE enables the vehicle fleet's data management by keeping track of mapbased positioning, mileage, uptime, and diagnostic codes, this solution has its limitations. WICE does not support streaming of data to other applications to enable real-time data analysis. Therefore, an additional architecture was also used to track real-time car events and measure driver behavior. Software has been developed to pipe selected signals from WCU to a centralized server inside the Volvo cloud via a WebSocket tunnel. This centralized server runs the back-end JavaScript environment, Node.js, and serves as a host for the WebSocket data tunnels, a web server, and data persistence in the attached PostgreSQL database. A benefit of using Node.js is that JavaScript runs on both the front and back-ends, enabling the reuse of code and variables.

Upon receiving signals, this server can perform the business logic and then choose to persist and forward data. To enable real-time communication with drivers, this server has additional WebSocket tunnels toward the in-car devices. These devices could be anything with a web browser. In this set-up, iPhones were used, locked into a custom-built app that provides a fullscreen web container. When these devices browse to the cloud server, they authenticate and verify the car VIN number they are associated with. Once initialized, the phone will receive data payloads through the WebSocket tunnel, and the information, according to the designed logic, will be displayed to the driver. In this case, WebSockets are preferred over a more traditional client long polling system. With WebSockets, the server controls when connected clients should receive new information. Besides, a WebSocket communication failure can be detected instantly by both the server and the clients. Fig. 8 shows the architecture of realtime vehicle signal processing for the Driver Coach app.

Limitations of the provided architecture and set improvements:

1. Due to the Volvo platform's inability to support the data transferring process outside the vehicle, the WICE system as the intermediate solution has to be used, which requires additional instrumentation for each test vehicle with the WCU unit. This does not allow the OEM to expand the study to the whole vehicle fleet of real users. The OEM's employees who use instrumented vehicles and share the data might cause a bias, often being far more experienced in using support systems due to their work tasks and engineering background.
2. The Over-The-Air (OTA) updates were initially not implemented, despite the cloudbased architecture. To perform A/B testing of the applied algorithm logic, the test car needed to pass the service point to update the software. However, with the increased number of changes during the test period, the OTA updates were implemented by changing the RP task and deploying a new RP task to the app autonomously. The RP task change will lead to the app restart from the user side, which is also performed automatically.
3. Another problem we encountered during the study was the lack of logging for the app performance from the user side. This left us unaware of the following problems: the phone cable connection, the phone battery level, the app connection, and functioning during the driving sessions. Therefore, we added additional logging to pin the phone at the beginning of each driving activity to check the phone's connection to our services. The true/false value reported to the server helps to understand if the driver got support in a particular driving activity or not. The continued disconnection problem could also be easily detected on the server side. With this logging in place, we could quickly identify and react to various connection problems, which helped us provide better app performance for the end-user.

Driver Coach app for PA: The front-end design

The Driver Coach app's communication is organized as a one-way systems output to the driver. The app's output is provided on the iPhone screen, stationary mounted to the instrument panel (see Fig. 9). In our set-up, the phone works as a one-screen application, where all notifications are displayed.

Since our logic counts seven events to be transmitted, seven graphical layouts were developed, including one layout to communicate the misuse of PA, four layouts to warn drivers about critical conditions for PA, and two layouts to promote PA in sparse and dense traffic conditions.

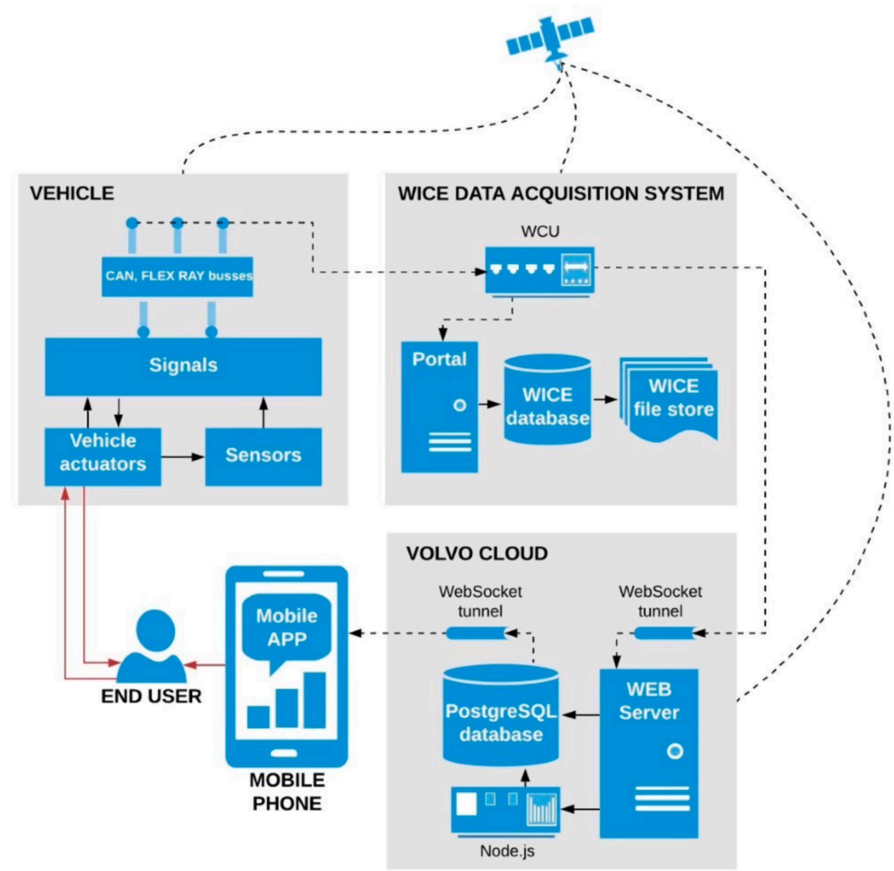

Fig. 8. The back-end architecture of real-time vehicle signal processing in the PA Coach app.

Fig. 9. The app's screen placement in the instrument panel.

We combined the following output techniques to draw driver attention to the PA Coach messages: a discreet sound at the beginning of the notification, a voice message, change of graphics/colors on the app screen, and motion design. Drawing from the findings of Biondi et al. (2014), which underscore the potential disruption caused by a sudden acoustic stimulus during driving, we have deliberately selected a discreet sound for notifying drivers about the start of our coaching service. This signal comprises two high-valence notes, imitating the unobtrusive sound of the system connection. It exudes a calming and neutral tone, carefully designed not to induce stress in the driver. Importantly, it plays only once without repetitions. Furthermore, due to driver safety regulations focused on eliminating driver distraction, the output needed to be designed in a way that minimized the need for reading from the screen. Since reading provides more distraction than listening (Stutts et al., 2003), voice messages are designed to provide drivers with information that is difficult to convey by using graphics without text. Still, we worked on shortening the voice message's length to make them as short and precise as possible.

Finally, graphics, color changes, and the motion design convey the message through the visual change on the app's screen. The on-screen change could be a standalone, independent solution for drivers discomforted by voice notifications or drivers who have already learned what the graphics mean. For these drivers, the phone volume can be decreased or switched off.

The final front-end design is shown in the Appendix 2 (Fig. 1). The red color represents driver mistakes, the orange the changing context that requires driver attention (warnings), and the green indicates the recommendations for PA usage in different conditions.

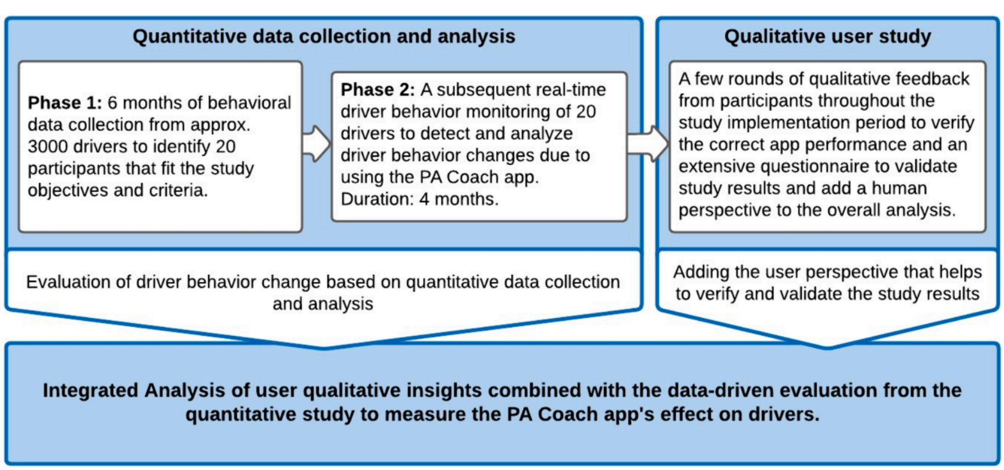

Fig. 10. Explanatory Sequential Mixed-Methods design.

Driver Coach app for PA: Study method

An Explanatory Sequential Mixed Methods (Creswell, 2014) approach is adopted in this study. The sequential use of quantitative and qualitative approaches (see Fig. 10) aims to facilitate integrated analysis of the PA Coach app's effect on drivers.

The explanatory sequential design has two distinct phases. During the first phase, quantitative data was collected and analyzed. The analysis of quantitative data helped in detecting relevant individuals for the study. Subsequently, quantitative data analysis is used to compare driver behavior before and after the Driver Coach app installation in participating vehicles. The quantitative data collection and analysis are based on the Volvo internal Naturalistic Driving (ND) study. Since all metrics were created based solely on vehicle telematics data, this study allowed unobtrusive behavioral data collection from drivers in their natural driving environment.

In contrast, qualitative data collection and analysis were performed to validate the quantitative analysis outcome and add the human perspective to the drivers' overall experience with the Driver Coach app for PA. The qualitative study has been designed to investigate the root causes for detected behavioral changes before and after the PA Coach app installation to enrich the data-driven insights with drivers' subjective reflections about the Driver Coach app for PA.

Quantitative study design

In the quantitative study, driver-system interactions were monitored together with contextual information, including the weather, road, and traffic conditions, to understand the context under which these interactions occurred. This type of analysis enabled the identification of different use patterns regarding the evaluated function and helped in drivers' categorization regarding their PA use strategies.

Participants

The driver categorization regarding the level of PA use was performed based on the historical data set, which includes driving data on more than 3,000 drivers over six months. All drivers were assigned to nine different categories. Driver categorization was made based on two main parameters: the extent of PA usage and the traffic conditions when PA was used. Additionally, the screening process of drivers included multiple parameters. First, the drivers whose measuring period (usually around a year) was coming close to the end were excluded. Second, only drivers from categories 1–3 were invited onto the study since their use strategy for PA usage can be improved significantly with the Driver Coach app's help. Third, only individuals who stated they are not sharing their vehicles more than 25 % and commute daily were accepted. Fourth, only drivers who agreed to participate in the study and share their personal data were included. Fifth, we deliberately looked for and added female participants to consider potential gender issues with the application.

Finally, the number of participants was limited to 20 due to the number of equipment sets supporting the Driver Coach app performance. As a result of the screening process, 20 participants were selected. Table A3 in the Appendix 1 shows drivers chosen for the study together with their screening criteria.

Furthermore, since this study was conducted based on the Volvo internal test fleet, all drivers were Volvo Cars employees with long-term experience of driving Volvo vehicles. However, despite their experience with the Volvo vehicle, all selected drivers were random VCC employees and not educated test drivers. These drivers were chosen because they showed extremely low to no usage of PA function while having long-term access to the functionality. Such behavior proves that their experience with cars has no relation to PA use behavior.

Additionally, Volvo employees directly involved in the PA development, evaluation, and testing process at Volvo were not accepted onto this study to exclude direct professional bias.

Study design and procedure

The data collection in this study was conducted in two phases: during a six-month period, from April to September 2021, and during a four-month period, from January to April 2022. In the first phase, the data from more than 3,000 vehicles were extracted and analyzed. This step helped detect relevant drivers for the study and enabled evaluation of their PA usage before the Driver Coach app installation. In the second phase, after the PA Coach app was installed, continuous monitoring of PA use behavior for the four additional months was performed to assess the effect of the Driver Coach app on the drivers' behavior.

Both phases considered driver behavior, PA performance, and driving context, simultaneously, to understand the frequencies of using PA and the driving context when driversystem interactions happened. Every trip was coded with a unique ID number, allowing separate evaluation. Data points that described each trip (time and date, vehicle speed, driving distance, etc.) were used to categorize driving activity and calculate the PA usage time in the complete trip. PA driving context was extracted using numerous signals from vehicle sensors, e.g., wiper sensors, fog lights, ambient temperature, speed limit signs, lane markings detection, turn indication, distance to the vehicle in front, etc. The analysis of this context data in our study supports the understanding of under what circumstances the driver performed activations or deactivations of the PA. Table A4, presented in the Appendix 1, describes context variables measured to assess the PA driving context.

Data retrieval and data pre-processing

The data collection was conducted using a WICE system (see Fig. 1). The WICE system enabled the management of the vehicle fleet's data by keeping track of mileage, uptime, and diagnostic codes. The raw data consisted of data from the Controller Area Network and Flex Ray busses and was collected for every trip. All driving activities, including activities with no PA activations, were included in the evaluation. Every driving activity was recorded and documented with a unique file name to connect the vehicle to its data and enable the assessment of every driving activity separately. During the data pre-processing phase, an evaluation of data quality was conducted. This assessment examined six dimensions of data quality, specifically accuracy and completeness of the data signals utilized in the framework, consistency and timeliness of logging signals, and validity and reliability of the logged data. Subsequently, a data cleaning process was employed to eliminate corrupt or inaccurate records from the dataset before analysis. Additionally, the data was synchronized in time to establish the appropriate order and structure for the initial dataset.

Data analysis

The quantitative study was performed in two phases. First, the complete ND study data set was analyzed, which helped to detect drivers whose behavior regarding PA use could be improved. Then, after drivers agreed to participate in the study, the additional screen for the PA Coach app was installed in their vehicles, and the Driver Coach app was activated. After that, the drivers' performance was uninterruptedly monitored and recorded to see the Driver Coach system's effect on their behavior.

In the main phase of the quantitative analysis, we collected data from 4704 driving activations, of which we analyzed 981 PA activations over a four-month measurement period. A comparative approach was used to record and observe any changes in drivers' behavior before and after they started using the Driver Coach app for PA. For this reason, the same set of metrics was used for the "before" (baseline) and "after" (treatment) evaluations. The data analysis was conducted with Power BI software for statistical analysis (Power BI Microsoft, 2022). The data were analyzed in three levels: onedriver evaluation (focused on the in-depth understanding of one driver behavior change), two groups comparison (based on the comparison of user behavior between identified user groups), and overall assessment (based on average calculation for all study participants).

Qualitative study design

The qualitative study was used to verify the results based on quantitative data analysis and enrich them with drivers' subjective opinions about the app. For that purpose, we conducted two in-depth questionnaires, one before the study started and another after four months of using the PA Coach app to capture driver experience without and with the Driver Coach app, obtain drivers' reflections, and explanations on the recorded behavior change and support provided. This helped uncover the human aspects affecting PA usage and the Driver Coach app.

Participants

Twenty drivers chosen based on the initial screening shared their opinion about PA function, their experience with it, and their understanding of PA abilities and limitations. After participating in the quantitative study, the same drivers were invited to triangulate data-driven results with their qualitative feedback.

The participants were recruited via corporate email on both occasions. Each time they clarified data sharing and connected to the previous agreement to share their data. In total, 17 drivers took part in the qualitative assessment, 4 females and 13 males aged 45–65 years (Mean 51.65, SD 6.42). According to participants' estimation, 14 drivers were sole or primary drivers who only shared a vehicle for 0–10 % of total driving time, two drivers rated car sharing at 15 %, and four reported 20 % car sharing. Although most drivers had the PA on board for more than a year or two, 35 % of drivers said they had never used PA.

Study design and procedure

As a data collection method, extensive questionnaires before and after the study are an effective and reliable choice for gaining knowledge on user behavior, user perceptions, and user satisfaction regarding coaching support. Additionally, several feedback sessions during the Driver Coach app use period were conducted to capture drivers' experiences. Through those sessions, users could openly talk about the Driver Coach app performance, their own performance, different road situations, etc.

The first round of qualitative study was conducted in September of 2021. A set of questions for the first round was uniform, meaning that all drivers answered the same set of questions to show their general attitude toward the PA function, their experience, and PA use strategies. With this data, we captured the initial driver state before the Driver Coach app implementation, and triangulated drivers' perceived behavior with their recorded behavior.

The second round was completed in May 2022. This time, the set of questions was designed based on individual behavior recorded in phase 2 of the quantitative study. Apart from the general questions, different users received customized questions, depending on their behavior changes. This approach helps clarify and verify the data-driven reasoning and digs deeper into the individual issues discovered instead of staying at the general level of understanding (Orlovska et al., 2019). Furthermore, the participants were encouraged to provide open-ended insights, elaborating on their experiences at the end of each questionnaire.

Integrated analysis

Subsequently, an integrated analysis of qualitative and quantitative insights was made to measure the Driver Coach app's effect on drivers and their behavior. This effect was estimated from three main perspectives:

1. Measure the increase/decrease of PA usage after the Driver Coach app installation.
2. Evaluate the change in driver behavior use strategies with PA.
3. Assessment of the perceived usefulness of the Driver Coach app for the drivers.

The main success criteria set for the evaluation are presented below:

- Drivers start using PA more
- Drivers make fewer mistakes while using PA
- Drivers reduce the use of PA in critical conditions connected to different warnings (drivers become better at understanding PA limitations
- Drivers have a positive attitude towards this type of active coaching, considering it to be meaningful and useful.

Driver Coach app for PA: Study results

This chapter describes the synthesis and analysis of the quantitative and qualitative findings, aimed at understanding the effect of the Driver Coach application on the overall driver behavior regarding PA function.

The final analysis is based on data from 17 drivers. Data from three drivers (two male and one female) were excluded due to poor data coverage from their cars. Their interruptions in using the app happened due to changing their car and going through the deinstallation/reinstallation processes that took them off the study for more than a month.

The overall level of PA usage has increased

To support this statement, three parameters were considered: the number of driving activities with PA activations, the number of total PA activations, including multiple activations within one driving activity, and the activation duration time.

The number of driving activities where the PA was activated increased.

The average use before the Driver Coach app support was 2.26 %, with slight deviations around this average. The monthly average of Driving activities with PA activations after app installation gradually increased. The steady increase was seen throughout the entire four-month period, starting at 2.72 % and rising to 8.73 % (after three months of the app usage) (see Fig. 11).

The number of PA activations within one driving activity has slightly decreased.

The average number of PA activations within driving activities where the PA was activated remains at the same level, slightly increasing after the app usage. Hence, in the period from April to May 2021, the average number of PA activations was 3.65 activations per driving activity where the PA was activated. After four months of using the PA Coach app, the average number decreases to 3,45 activations per driving activity where the PA was activated (see Fig. 12).

The PA activation duration time has been increased

Since PA activation can last from a second to several minutes, it would be wrong to infer an increase in PA usage based on the number of activations alone. Hence, the duration of PA activation is another aspect necessary for the overall increase measurement. The activation duration time for PA is the actual time the driver spends with support. For April-September 2021, drivers used PA on average 3.85 % of total driving activity time where the PA was activated. For comparison, for the period from January to April 2022, PA activation duration time increased to 4.8 % (see Fig. 13).

A small decrease in the number of activations within a single trip and the increase in the activation duration time within one single trip showed a positive connotation when the PA was used for longer durations and in larger proportions of a single trip. This indirectly indicates the driver's improved ability to understand the PA context better. Drivers are able to select the suitable context for PA activations, enabling them to use the function for extended periods without experiencing automated interruptions caused by unfavorable conditions that would otherwise lead to PA deactivations.

In conjunction with the continuous rise of driving activities with PA

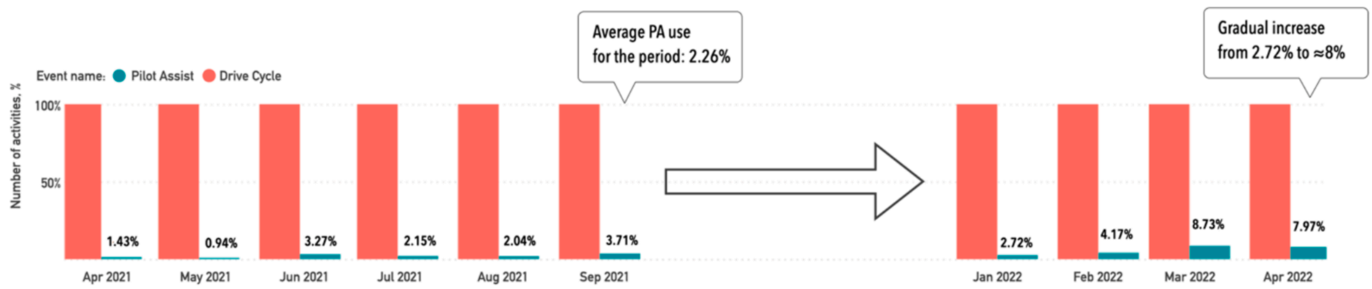

Fig. 11. Number of trips with PA activations before and after the Driver Coach app installation.

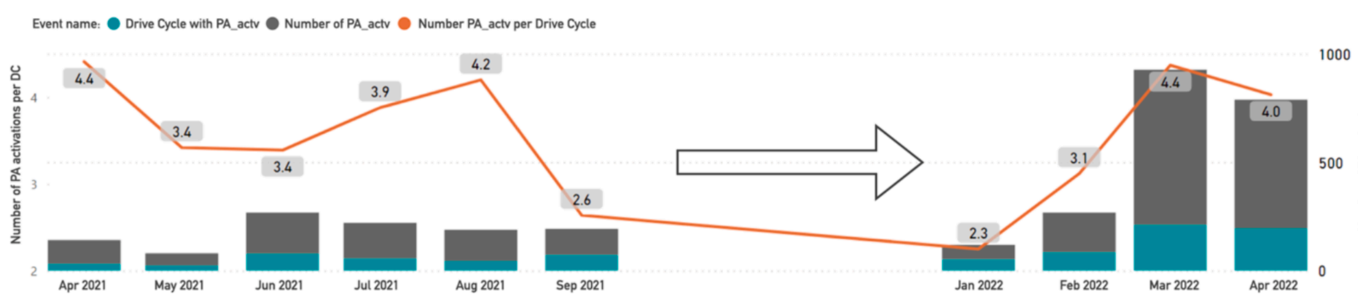

Fig. 12. Number of PA activation within driving activity where the PA was activated before and after the Driver Coach app installation.

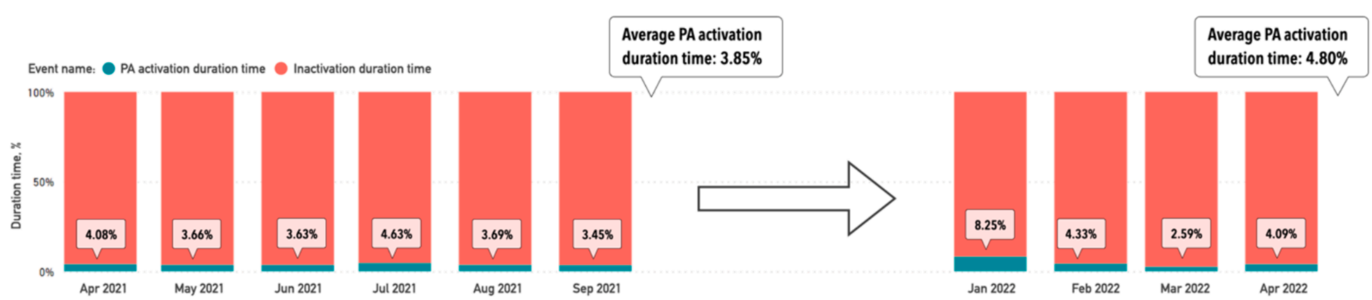

Fig. 13. PA activation duration time before and after the Driver Coach app installation.

activations throughout the entire four-month period after the app installation, these findings demonstrate the overall favorable impact of the Driver Coach app on the extent to which the coached function is used.

Different user groups present different improvement rates

Not all users present the same rate of improvement; some users improve faster than others. Therefore, we distinguished two user groups

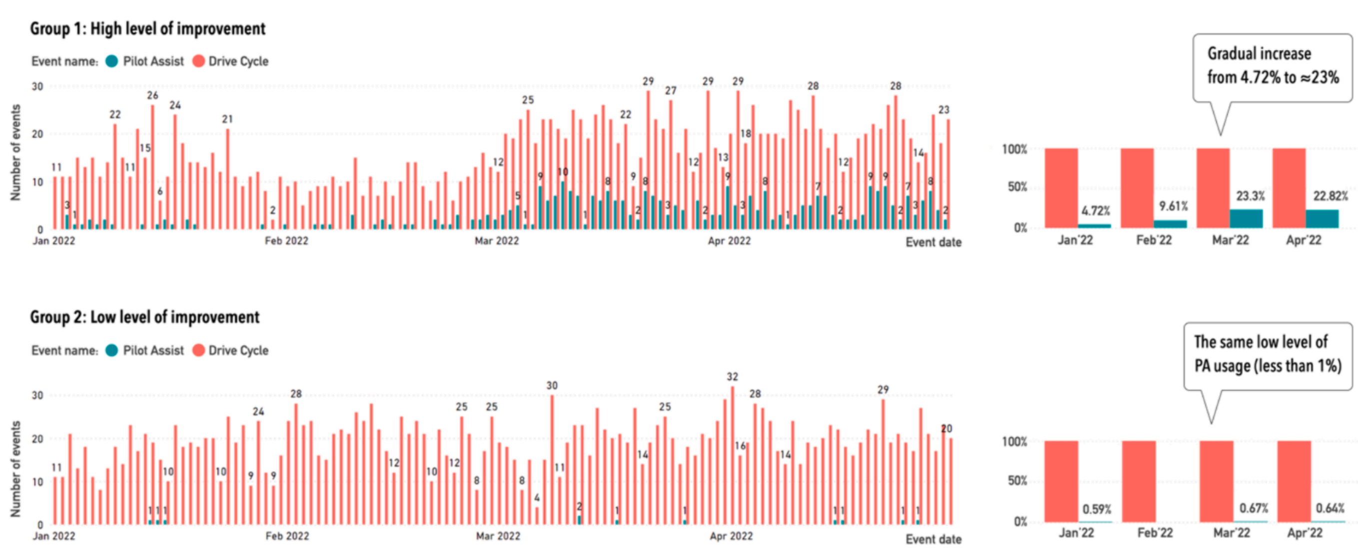

Fig. 14. PA activation duration time before and after the Driver Coach app installation.

with clear commonality in their improvement rates. The first group includes users that improved significantly and showed a higher level of PA use after four months of Driver Coach app usage (seven users in total). The second group contains users who remained on the same PA usage level and have not shown improvement for the corresponding period (seven users in total). Another three users stayed ungrouped since their data did not show a clear trend in their behavior.

As can be seen in Fig. 14, users from group 1 increased their PA usage from 4.72 % to 23.30 % for the four months with the Driver Coach app. Users from group 2 showed the same low level of PA usage (less than 1 %) with the Driver Coach app as before the app was installed.

Group 1 contains users with different starting points regarding their PA usage frequency. However, drivers from group 2 were drivers with no previous records on PA activations. The lack of improvement in PA use strategy for drivers from group 2 could be explained through two reasons:

1. They did not intend to improve their PA use strategy. Their previous negative experience with PA, low trust in automation, or neglection phase regarding the function, in general, could be a reason for no improvement. In this case, there is clear evidence that we need to engage drivers in the coaching set-up. The drivers' desires regarding the coaching, its extent, and the frequency of message output should be accounted for. If the driver does not want to use this type of support or feels that they have learned enough after some time, the driver should be able to deactivate the app, pause it, or change the coaching strategy. The only way to verify these assumptions is by collecting subjective data from these drivers.
2. The strategy for engaging new users with PA (explanation strategy of how to activate, navigate and follow the statuses) was not good enough for all app users. Some drivers might need a more detailed description of how the function works. In this pilot study, these verifications were not considered. We designed a universal strategy, trying to minimize driving distraction from the primary driving activity and simultaneously explain PA performance. The chosen balance could not be optimal for everyone. In the future, it would be good to investigate the need for further gradation of explanation strategy.

The consequent qualitative study revealed that both assumed reasons are present. Thus, two drivers claimed that they do not like using PA in general. This means that they are not well-targeted users for the PA Coach app. And since the PA is not mandatory, we should not expect a PA use increase from users with predetermined negative opinions about this function.

Another three users with no improvement claimed that they do not understand the messages on the screen, specifying that the message remains short time on the screen. This would be considered critical for the output design if users would not deactivate the sound volume. According to our vision, the voice message further explains the graphic. This is made for safety reasons so that the driver decreases the time looking at or reading from the screen. We recommended participants not deactivate voice messages before the meaning is understood, and the graphics become sufficient. Nevertheless, the "time on screen" should be further tested in future design iterations.

The effect of the driver Coach app on drivers' behavior

This section presents the effect of the Driver Coach application on driver behavior change. We consequently discuss the impact of mistakes, warnings, and recommendations on drivers developing new skills and behavioral strategies.

Concerns regarding speeding behavior

The average number of mistakes increases with the time of using the Driver Coach system. This increase comes from four drivers who built up the specific use pattern for using PA. In particular, these four drivers use the Mistake message as a warning only since it helps them to control their acceptable over-speeding level. If other drivers often deactivate PA when they have this warning, these drivers choose another strategy. They seem not to recognize the seriousness of the situation and keep the speed high, since their average reaction time on our message is 27 s, meaning that on some occasions they continue to over-speed for more than two minutes. Additionally, drivers 17, 20, and 22 present a pattern when multiple events happen during a single PA activation (see Fig. 15). This means that they reduce the speed for some period and then build up the speed again. This behavior is a clear indication that the warnings are useful for these drivers to control speeding that is acceptable to them.

It is important to mention that these drivers had history of speeding behavior even before they started to use the Driver Coach system. Nevertheless, their speeding occasions increased with the PA Coach app. We have the following explanation. According to our logic, we communicate a mistake when significant over-speeding happens (more than 20 km/h above the speed limit). This means that the Driver Coach app might stimulate the speeding of these four drivers since they feel they can speed until they are notified by the Driver Coach app. Thus, the behavior of these drivers with PA does not contribute to safe driving and should be the focus of further investigation. On the contrary, a study by Kontaxi et al. (2021) shows the positive effects of feedback about speeding behavior on motorcyclist riders. However, according to this study, drivers tend to reduce speed in the city area more often than on the highways. Therefore, we suggest that further research is needed. If it proves that our logic stimulates their speeding activities, then the logic needs to be reconsidered, even though it works well for the other drivers.

Using PA in a critical context

As for the driving behavior in critical driving conditions for PA, we can conclude that drivers from the pool were careful (maybe naturally) about driving with PA in critical contexts. We recorded six PA activations in "bad weather" conditions for a four-month period, one PA activation in "low visibility," and one PA activation in a "low-speed area" (see Fig. 16). The exception is the "slippery road" condition that happened quite often during the measurement period. The peak of "slippery road" warnings falls in March (106 records), which is logical, considering the weather change. However, further exploration of driver behavior changes in such small number of events would not make sense. We need to collect more data to come to statistically significant results for our analysis.

Furthermore, the average PA activation duration in "slippery road" conditions is two minutes, which is considerably higher than the same measure for the "over-speeding" condition, where the activation duration time is 27 sec. This time difference indicates that drivers understand the logical difference between a warning and a mistake. We want drivers to react when the mistake happens (reduce speed or deactivate PA), but we do not expect specific driver reactions to warnings like "slippery road," since our goal is to only raise driver attention to the driving situation and PA performance.

The effect of PA Coach recommendations

To conclude regarding Driver Coach app effectiveness, it is essential to understand if drivers can perform at the same level without Driver Coach app messages. Therefore, we looked at trips where PA was activated and the moment when these activations were made. In trips where the Driver Coach notification took place, we distinguished PA activations made before the notification took place, direct after (when the communicated condition was still lasting), and after the communicated condition was finished.

According to our calculations, the direct effect, which consists of activations that were made while the communicated condition still lasted, is equivalent to 15.75 % of total PA activations. The indirect effect, which consists of activations that were made after the communicated condition finished and before the driving activity is finished, is

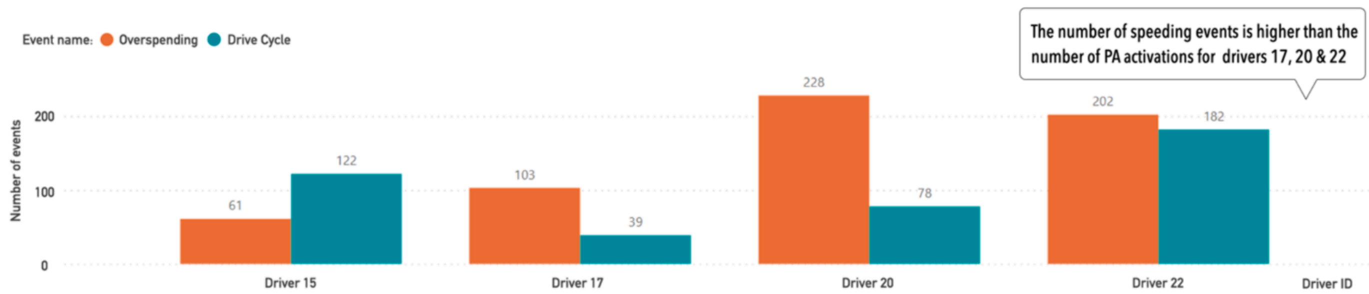

Fig. 15. Group of users with speeding behavior.

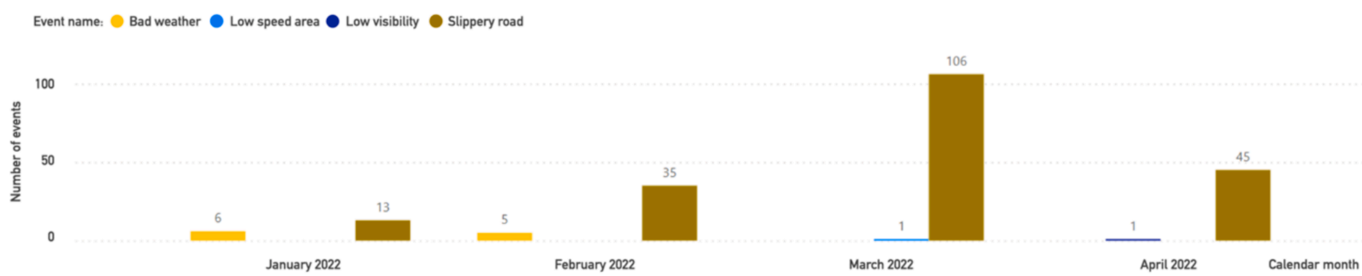

Fig. 16. Registration for PA activations in critical conditions.

equivalent to 15.07 % of total PA activations. The rest of the PA activations (69.18 %) happened before the Driver Coach notification took place or in support-free trips, as envisaged in our logic to anticipate drivers' learning rates (see Fig. 17).

According to our understanding, 69.18 % of the PA activations are less dependent on Driver Coach notification and indicate drivers' learned ability to implement Driver Coach recommendations without reminding them. Nevertheless, we admit that while the Driver Coach app is still in use, any PA activation could be seen as an effect of the app. Therefore, in continuing this study, it would be critical to deactivate the app for all users and measure their behavior strategy for a few additional months. If the PA usage trend remains at the same level, it will prove that the increase in PA use is not the effect of app notifications but the learning outcome of using the Driver Coach app.

Discussion and further improvements

This section explores the primary limitations of this pilot study and reflects on potential enhancements that could further improve the coaching support.

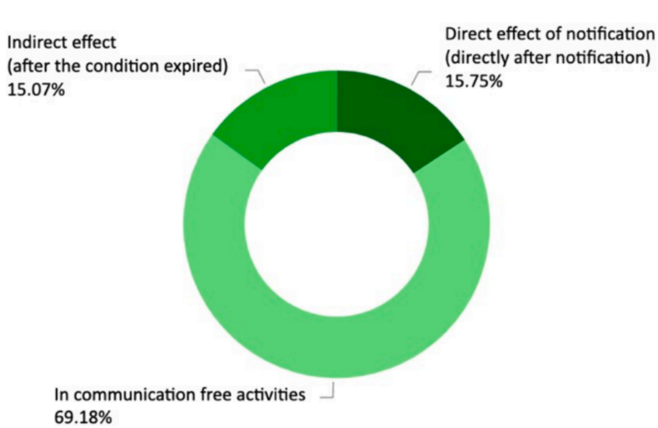

Fig. 17. Direct and indirect effect of Driver Coach app recommendations.

Limitations

Despite the results achieved in this study, a few months of development and consequent testing of the Driver Coach app revealed a few issues that delimit our study and affect the final outcome. In this section, we will discuss technical and user-related limitations.

Driver Coach app is not fully integrated into the vehicle infotainment system

Driver Coach app for PA is not embedded with in-vehicle apps and works independently of other built-in functionalities, leading to the following consequences:

1. Driver Coach app performance is network dependent. Even though WICE has direct access to vehicle signals through cable, the data is still transferred to the server, where the PA Coach software accesses it, uses it for internal calculations, and sends commands to the phone. This set-up creates two network dependencies from the car to the server and then from the car to the phone, since two devices must have good reception for the system to capture all events and perform all logic without delays. In the case of an integrated application, the whole algorithm could run inside the car without the network roundtrip, which would significantly improve the entire set-up.
2. The app does not consider other communication in the car and has a lower priority than built-in functionality. Therefore, it was not easy to ensure the timing for notifications was correct. Consequently, two voice messages (from the Driver Coach app and built-in system) can potentially output simultaneously, negatively affecting the user experience. Since the Driver Coach app could not monitor other notifications from built-in systems or services, neither could it redeem volume and consider the higher priority of the built-in functionality.

The use of the phone for the app screen

The use of the phone as the app screen is another limitation that we accepted for the pilot test. This resulted in the following issues:

1. A couple of days of not driving leads to the phone battery discharge. As a result, part of the driving activity or the whole of it (if the

driving activity is short) can be taken up with charging the phone's battery and powering up, thus providing no support to the driver.
2. No control over the proper connection. The phone can discharge, and the participant can disconnect it, switch it off, or leave the phone at home. As a result, we depend on drivers' engagement and discipline.

As a result, we implemented additional logging to better control the app connection and react quickly to the absence of data due to the phone disconnection.

We could not ensure unchanged settings for all cars during the whole study period

Since our study lasted more than a year, and the drivers who participated in the study were part of a bigger project at Volvo, we could not fully control eventual changes in the initial set-up. Such issues as quitting the job, planning extended car services, changing the car due to the end of the leasing contract, etc., resulted in several problems that we discovered "on the go" and needed to react quickly to in order to solve the issues and eliminate their negative effect on our study results:

- Some new car models had different signals logic implemented for the same functionality (iCUP cars based on Android), which resulted in a gap in the uninterrupted use time of the app until we found and implemented the universal logic.
- Due to the complicated delivery schedules, we could not arrange the de-installation and re-installation of the study's equipment during one workshop visit. The time between deinstallation and re-installation for some participants could spread out to a week, resulting in an extensive break in the study participation.
- No research proves that the use of PA remains the same across different models and generations of cars. A driver could decrease interactions with PA due to the adaptation period to the new car, or vice versa, or start exploring the functionalities they had never tried before.

All these issues resulted in a more extended transition period (from October 2021 to January 2022), when the dataset had many coverage problems. So, we decided to extend the study until May 2022 to have a four-month dataset with good coverage.

UI research was not the focus of this study

Although our users seem to understand the different expected reactions to mistakes and warnings, we have not focused on validating the app design with additional UI studies. For the pilot study, we were more interested in proving the feasibility of such a project rather than the UI design for it. Nevertheless, we did present our design to, and considered feedback from, the Volvo UX team, but we have not conducted specific user studies evaluating the Driver Coach design. We admit that this work is essential and needs to be done if the project is to continue.

Future work

This section discusses further improvements that could potentially enhance the functionality of the Driver Coach app and increase drivers' involvement with it.

Deeper personalization in coaching design could better fit individual needs

Another improvement could be in considering drivers' individual preferences regarding the support. This might relate to the amount of information the driver needs, the way he/she wants to receive the notifications, the prioritization of the key benefits from the function use, which can differ from driver to driver. For example, in a study by He et al. (2010), the authors bring forward the idea that an improvement of personalized communication would be to consider the specific values and goals of each individual when providing feedback. The visualization could provide personalized feedback highlighting different aspects, depending on the driver's individual points of interest and prioritized values, such as increased safety, lower CO_2 emission, or fuel economy. A study by Stillwater and Kurani (2013) concludes that the display's information content plays an important role in stimulating drivers to drive economically. Their study showed a significant difference in the decrease of fuel consumption depending on feedback design. Anable (2005) proposes segmenting drivers based on such psychographic variables as driver attitude, values, and personal norms, instead of such demographic variables as gender or age. This is in line with the common approach of consumer behavior and marketing presented by Wedel and Kamakura (2000), which is based on the idea that different people need to be approached differently because they are motivated by different factors. However, the described works mostly remain theoretical, since deriving driver state and preferences in a natural driving environment is poorly developed in the automotive area. Such restrictions as GDPR classify these types of data as personal, delaying the development of driver-related metrics, which negatively affects the development and testing of different models utilizing this type of data. Thus, the question of whether adapting feedback technology to different segments of drivers with specific psychographic characteristics will increase the acceptance and effectiveness of personalized feedback is still open.

This type of coaching should be optional

The OEMs are interested in promoting the use of functions such as PA. They want them to be used and appreciated. However, the amount of feedback currently provided as output for the driver is usually minimal. One of the reasons is that safety restrictions require minimum distraction from the output design to ensure high driver engagement on the driving task. Another reason is the multitude of systems that are used at the same time. If all systems provide detailed feedback, the significant volume of information will increase the driver's mental workload. So, any output needs to be optional and should depend on the driver's desire to learn the system better. Ideally, the driver should manage the coaching support settings and be able to increase/decrease the level of support, the frequency, and the way information is output. In addition, the coaching should be optional. Drivers should be able to deactivate coaching when they feel it is not appropriate, think that they have learned enough, are carrying passengers, etc. As our study reveals, if a driver does not want to improve, it is most unlikely that she/he can be forced to. Through pestering, the coaching will mainly cause irritation and distraction from the primary driving task.

The use of historical data for driver categorization is not necessary

The modular development helped us understand that we do not need to know a driver's previous behavior. We can set the driver category to 1 for all drivers, deactivate steps A, B, and D (see Fig. 2) for the time required for category 1 to 9 updates, and see how the system updates drivers' categories based on their PA usage. At some point, the driving category will stop improving. This would mean that the driver category is identified.

This automated category identification has not yet been tested and verified since we were initially interested in drivers in categories 1–2 and, therefore, chose them based on those categories. Still, there is great potential to transfer this app to a fully automated application that requires no preliminary knowledge about users to provide feedback.

Additionally, it would be helpful to add to the app logic such parameters as driving style, state, and workload, which were not assessed in this pilot study due to personal data collecting and handling issues. However, if we could arrange the logic whereby these data are used in direct calculations without pre-saving sensitive data in temporary databases, we could avoid the GDPR issue and open up better opportunities for coaching strategy improvement and a better choice of time for communication.

Conclusions

This paper presents the Driver Coach app for PA from its design to the complete implementation to validate the logic design and impact of real-time coaching on driver behavior. A paper describes how the fully functioning app gathers diverse data from actual driving, enforces real-time data analysis, considers the driver's reaction to the PA Coach notifications, and reflects on eventual changes in driver behavior, adjusting communication strategy in real-time. Furthermore, the paper suggests logic improvements that are able to enhance the quality of driver support further.

Besides the logic validation, this paper analyzes the impact of the Driver Coach app on driver behavior related to the Volvo Pilot Assist (PA) function. The overall results show a steady increase in PA usage. Thus, the number of driving activities with PA activations has gradually risen from 2.26 % to 8.73 % during four months of app usage. Furthermore, the activation duration time of PA activation within a driving activity is also increased, even though the average number of PA activations within one driving activity has slightly decreased. Different user groups had varying improvement rates, with some showing a significant increase in PA usage (from 4.72 % to 23.30 %) while others remained at the same level.

The Driver Coach app also had an impact on driver behavior. Safety concerns related to speeding behavior were noted and discussed, with some drivers treating the Mistake message as a warning instead of reducing their speed. Future studies should further verify this issue and reflect on it in the logic design if the relation between logic design and speeding behavior confirms.

Apart from the speeding behavior, the Driver Coach app has a positive impact on driver behavior. After using the coaching application, the drivers could implement the recommendations independently, indicating positive learning outcomes. Approximately 69 % of all PA activations occurred due to the driver initiative and not due to the app notification. However, it is important to note that this study is a pilot study. Further research is needed to determine whether the increased PA usage is due to app notifications or the learning outcomes of using the Driver Coach app. A subsequent study, where drivers' behavior is observed after deactivating the Driver Coach app, would provide a comprehensive understanding of the learning outcomes and the app's impact on driver behavior.

CRediT authorship contribution statement

Julia Orlovska: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Casper Wickman:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Rikard Söderberg:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Daniel Bark:** Data curation, Software. **Christoffer Carlsson:** Data curation, Software. **Pär Gustavsson:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix 1

Table A1
PA Drivers' categorization.

Driver category	Description	Sparse traffic	Dense traffic
Category 1	Drivers who almost do not use PA	0–5 activations	0–5 activations
Category 2	Drivers who use PA only in sparse traffic conditions and to a low extent	< average level	0–5 activations
Category 3	Drivers who use PA in both sparse and dense traffic conditions to a low extent	< average	< average
Category 4	Drivers who use PA only in dense traffic to a low extent	0–5 activations	< average
Category 5	Drivers who use PA only in sparse traffic conditions to a high extent	≥ average level	0–5 activations
Category 6	Drivers who use PA in sparse traffic to a high and in dense traffic to a low extent	≥ average level	< average
Category 7	Drivers who use PA in dense traffic to a high and in sparse traffic to a low extent	< average	≥ average level
Category 8	Drivers who use PA in both sparse and dense traffic conditions to a high extent	≥ average level	≥ average level
Category 9	Drivers who use PA mainly in dense traffic to a high extent	0–5 activations	≥ average level

Table A2
Design of communication messages.

Code	Message	Additional message/Explanation
F(R1)	You have good conditions for Pilot Assist. Take the opportunity to activate it. Browse to Pilot Assist using the steering wheel's arrow keys.	Please monitor the Pilot Assist status changes on the DIM. When the steering wheel in the middle is green, Pilot Assist is active. When the steering wheel turns grey, Pilot Assist runs, but the steering assistance is not active.
F(R2)	Pilot Assist can be very helpful in dense traffic conditions. Please take the opportunity to activate Pilot Assist.	Set the desired speed and the time distance to the vehicle in front, and Pilot Assist will help you adjust the speed regarding the moving objects in front and keep your car within the road lane.
F(W1)	You entered a low-speed area. Please be extra cautious while using Pilot Assist here. It might have trouble detecting people or other moving objects in front.	
F(W2)	The system has detected the fog lights activation. Please be extra cautious when using Pilot Assist in poor visibility conditions since it has a high risk for Pilot Assist deactivation.	
F(W3)	Wiper sensors indicate heavy rainfall. Please monitor the Pilot Assist status changes since high precipitation may cause Pilot Assist deactivation.	
F(W4)	The temperature outside and the wiper sensors indicate the possibility of slippery road conditions. Please be extra cautious. Pilot Assist might need your help to handle these road conditions.	
F(M1)	You are significantly over-speeding while using Pilot Assist. Please reduce your speed according to the speed limit signs. Note that Pilot Assist also has an emergency response time.	

Table A3
List of participants.

Participant N_o	Gender	Age	Car model	Driving frequency	Car sharing	PA usage	PA availability
Participant 1	Male	59	XC60 T8	6–7 days a week	5 %	Yes	more than 2 years
Participant 2	Male	61	S60	6–7 days a week	0 %	Yes	more than 2 years
Participant 3	Male	50	XC60	6–7 days a week	5 %	Yes	more than 1 year
Participant 4	Female	56	XC60	6–7 days a week	10 %	No	more than 1 year
Participant 5	Male	60	XC40	6–7 days a week	5 %	Yes	more than 2 years
Participant 6	Female	48	XC60 T8	6–7 days a week	20 %	No	less than 6 months
Participant 7	Male	50	XC60 T8	6–7 days a week	15 %	Yes	more than 2 years
Participant 8	Female	47	XC60	6–7 days a week	10 %	Yes	more than 2 years
Participant 9	Male	47	V90	6–7 days a week	10 %	No	more than 2 years
Participant 10	Male	48	XC60	6–7 days a week	5 %	Yes	more than 1 year
Participant 11	Male	60	V60 T8	6–7 days a week	10 %	No	more than 2 years
Participant 12	Male	50	XC60	6–7 days a week	15 %	Yes	more than 2 years
Participant 13	Male	50	S60	4–5 days a week	20 %	Yes	more than 2 years
Participant 14	Male	65	V60	6–7 days a week	20 %	Yes	more than 2 years
Participant 15	Male	50	XC60 T8	6–7 days a week	5 %	No	more than 1 year
Participant 16	Male	52	XC90	4–5 days a week	10 %	Yes	more than 1 year
Participant 17	Female	45	XC60	4–5 days a week	20 %	Yes	more than 1 year
Participant 18	Male	52	XC60 T8	6–7 days a week	5 %	No	more than 1 year
Participant 19	Female	39	V60 T8	6–7 days a week	5 %	Yes	more than 1 year
Participant 20	Male	44	XC40	4–5 days a week	0 %	No	more than 1 year

Table A4
Summary of data variables for the PA driver behavior evaluation.

Driver-related variables	Description
Number of Drive Cycle (DC)	per day/week/month to understand the level of activity;
Time of DC start	number of activations within one single DC;
Duration of DC	to understand the type of the trip;
Frequency of PA/ACC usage	to count activations withing one DC;
Duration of PA/ACC usage	to calculate the activation duration for PA/ACC;
Time of act./deact.	to understand the type of the trip;
DC length	to understand the type of the trip;
DC type	to understand the type of the trip;
Turn indication	to foresee driver intention to perform the maneuver;
GPS location	to map driver behavior to the driving context in the zoom-in analysis.
Context variables	Description
Wiping status	to detect heavy rain or snow;
Fog illumination	to control visibility on the road;
Ambient temperature	to exclude slippery road conditions;
Lane marks reading	a precondition for ADAS performance;
Speed limits	to identify the road type;
Driving speed	to see the deviation from speed limits;
Braking/Acceleration	to determine the distance between changes;

(*continued on next page*)

Table A4 (*continued*)

Driver-related variables	Description
Distance to the vehicle in front	to identify condensed traffic;
Vehicle/System(s) variables	Description
ACC performance	on/off/standby mode – contributes to PA performance;
PA performance	on/off/standby mode;
PA availability	the signal tells you if LatCtrl is OK to activate;
Radar On/Off	the signal from the radar ensure the ADAS performance;
Camera On/Off	the signal from the cameras ensure the ADAS performance;
Coach App responce	the signal that returns true/false connection value in every DC;
Vehicle Metadata	model, market, year of production, vehicle-specific configuration, etc.

Appendix 2

Fig. 1a. Front-end design for Driver Coach app (from left to right: PA_off status, Recommendation event – Sparse traffic, Recommendation event – Dense traffic, PA_on status).

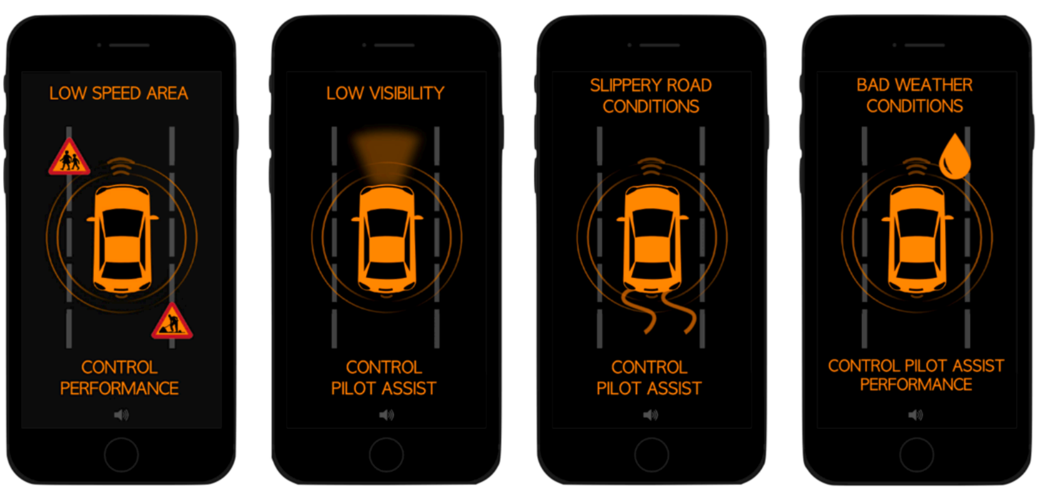

Fig. 1b. Front-end design for Driver Coach app (warnings layouts).

Fig. 1c. Front-end design for Driver Coach app (mistake layout).

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