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An interview study exploring Tesla drivers' behavioural adaptation

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ABSTRACT

Partially automated vehicles (PAVs) have been used in real-world environments for several years since the emergence of autonomous driving. It is important to understand the effects of partial automation systems (PAS) on the understanding of drivers and their behaviour during the first months of use. In order to adapt to new vehicle technology, drivers usually exhibit specific behaviours in this stage that are not intended by the developers, namely *behavioural adaptation.* The present study investigated the behavioural adaptations by early PAV adopters after short-term usage. A semi-structured interview was conducted among 20 Tesla drivers who had relatively high experience (one to five months) with Autopilot, and the interviews were synthesized to understand their behavioural adaptation, mental models, and trust during the period of use. The results showed that PAV drivers had a very positive attitude towards the PAS and drivers universally engaged in secondary tasks during automated driving. They also learned from their experiences to identify relatively safe usage conditions and they employed a safety margin to avoid exposure to excessively risky situations.

1. Introduction

The advanced driver assistance systems 'Combined Function Automation' (NHTSA et al., 2013) and 'Partial Automation' (SAE, 2014; Gasser and Westhoff, 2012) have been introduced onto the market to assist driving, where they simultaneously allow both longitudinal and lateral control. It is considered that autonomous driving systems have the potential to improve the wellbeing of drivers and increase safety by preventing driver errors on public roads (Stanton and Marsden, 1996; Driel and Arem, 2010; Doecke and Anderson, 2013).

However, a fatal accident in the USA was strongly associated with the misuse of a partial automation system (PAS) (NHTSA, 2017), and several non-fatal crashes have also been linked with a delayed reaction or misuse of this automation system (Tesla Motors Club, 2016a, 2016b). The behaviour of drivers when using a PAS might have caused these traffic accidents.

Under current PAS rules (Level 2 automation; see SAE, 2014), drivers are required to continuously monitor the system and be prepared to take over at any time in case the system reaches its technical limits or a malfunction occurs (Gasser et al., 2016). Thus, the driver's task has changed from active driving to supervising the PAS with occasional intervention.

In laboratory settings, researchers have found that driving with a PAS is a more difficult task for humans than manual control due to side effects caused by the PAS, such as decreased vigilance (Kaber and Endsley, 2004), skill degradation (Merat et al., 2014), overreliance or complacency (Beller et al., 2013; Helldin et al., 2013), or reduced situation awareness while engaging in a secondary task (de Winter et al., 2014). During manual driving, engaging in a secondary task takes the visual attention away from the forward roadway and it could increase the likelihood of a near-crash/crash (Simons-Morton et al., 2014). Klauer et al. (2006) found that glancing away for more than 2 s for any purpose could increase the near-crash/crash risk by at least two times compared with normal baseline driving.

In many PAS studies, drivers experienced automation systems for the first time over a short period of time (generally less than 30 min; Naujoks et al., 2015; Sibi et al., 2016; van den Beukel and van der Voort, 2017). During this short period, it is likely that drivers are not able to integrate the behavioural changes caused by the PAS into their normal behaviour (Wege et al., 2013). Therefore, it is important to explore the actual behaviour of drivers after interacting with the PAS for a relatively longer time period (one to five months).

1.1. Behavioural adaptation

During a certain period of interaction, in order to adapt to new vehicle technology, drivers usually exhibit specific behaviours that are regarded as behavioural adaptation (BA). BA mainly describes behaviours that are not intended by the initiators or developers of the change (OECD, 1990). Typically, the different forms of BA that have

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negative effects on safety are of most interest to road safety researchers and policy makers. It has been shown that most drivers need a period of about two weeks to learn how and when to use an in-vehicle system (Weinberger et al., 2001; Viti et al., 2008). Therefore, BA can be viewed in several stages (Manser et al., 2013; Wege et al., 2013) where the two main phases are the 'learning and appropriation phase' and the 'integration phase' (Cacciabue and Saad, 2008). Studies using laboratory simulators have mainly observed BA in the first phase of using adaptive cruise control (ACC) that partly automates longitudinal car control. They raised concerns about poorer lane discipline, sudden reactions to safety-critical events, increased speed, or decreased time headway (Nilsson, 1995; Dragutinovic et al., 2005; Young and Stanton, 2007). In general, these studies mainly demonstrated that driving safety was negatively influenced by the use of ACC for a limited period of time.

However, other studies have focused mainly on BA in the 'integration phase' using large field operational tests (FOTs) where the behaviour of experienced vehicle-technology drivers was recorded on real roads. FOT studies have shown that the potential for adverse BA was not as serious as that found in tests using simulators (Benmimoun et al., 2013), where the drivers exhibited particular self-regulatory behaviours such as keeping the system deactivated under dense traffic conditions (Pauwelussen and Feenstra, 2010).

Nevertheless, research has shown that the drivers of vehicles with ACC are more likely to engage in secondary tasks than non-ACC drivers, especially when they became familiar with this system (Malta et al., 2012; Bianchi Piccinini et al., 2012; Huth et al., 2012). Thus, the exploration of BA needs to focus more on the 'integration phase' (Patten, 2013).

The cognitive process that underlies these behaviours in the dynamic process has been explained by a qualitative model of the BA framework (Rudin-Brown, 2010; see Fig. 1). This model indicates that:

> '*Drivers who are more likely to trust a device are predicted to be more likely to change their mental model of the driving task. This change in the mental model would influence driving behaviour directly. Meanwhile, drivers' behaviour towards the vehicle-road system would, in turn, provide feedback to their level of trust.*'

In order to explore the BA of drivers in response to a PAS, the present study focused mainly on the mental model, trust, and BA associated with the PAS, and attempted to explain the formation of any observed BA under this framework.

1.2. Mental models

A mental model is defined as ' … a rich and elaborate structure, reflecting the user's understanding of what the system contains, how it works, and why it works that way' (Carroll et al., 1987) when a user is interacting with a system. The information in the mental model has analogical relationships with the external world and it allows people to make successful predictions (Brewer, 2003). Mental models of the driving task are closely related to the situation awareness (Stanton and Young, 2005) and BA of drivers (Rudin-Brown, 2010; Smiley, 2000). Accidents often occur when a driver's inaccurate mental model does not match the actual road situation (Cafiso et al., 2007; Lamm et al., 1999). The mental model of vehicle technology reflects how a driver understands its function and limitations, which they can then employ to decide when and where to activate or deactivate the system (Boer and Hoedemaeker, 1998).

In the area of mental model studies related to ACC, Beggiato and Krems (2013) showed that both the initial information and practice can help drivers build mental models of ACC during its use. However, most drivers do not actually rely on the user manual to form their mental models, and thus their mental models are formed mainly based on their experience through use, which often makes them tend to overestimate the helpfulness of ACC (Jenness et al., 2008; Piccinini et al., 2013). Moreover, a strategy that relies on trial-and-error practice alone is considered insufficient for developing an appropriate ACC mental model (Beggiato and Krems, 2013). In reality, even experienced ACC users often fail to fully understand the functions and limitations of the technology, which may cause serious problems in the worst case (Bianchi Piccinini et al., 2015).

1.3. Trust

Trust is ' … the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability' (Lee and See, 2004). Trust in technology is 'a cognitive attitude towards the respective technology that changes over time' (Lee and See, 2004). Trust is often considered a by-product of the perceived accuracy of a mental model of the technology (Beggiato et al., 2015) and an intermediate variable of behaviour (Comte, 2000).

Similar to a mental model, pre-existing knowledge and experience may influence trust (Hoff and Bashir, 2015). In addition, aspects of the driver's personality such as confidence and locus of control can also influence trust (Rudin-Brown, 2010; Walker et al., 2016). Driving

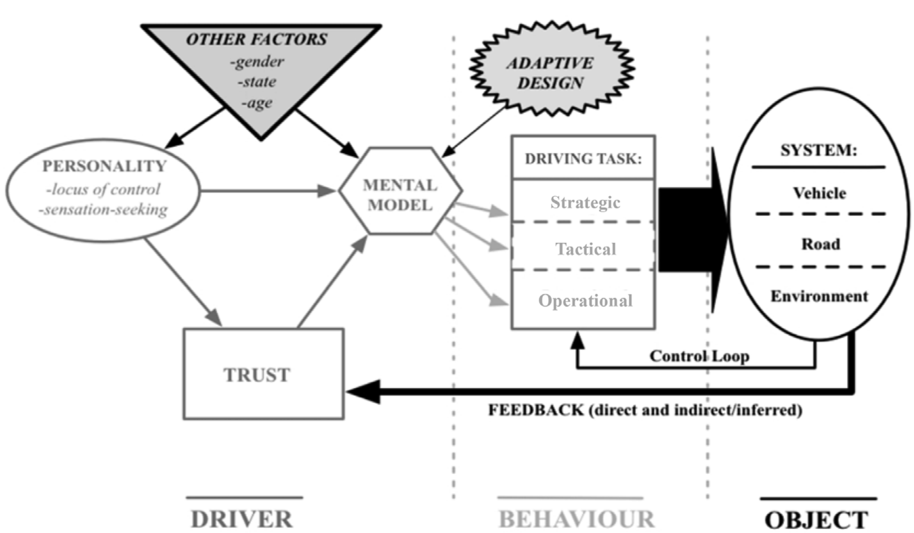

Fig. 1. Qualitative model of behavioural adaptation (Rudin-Brown, 2010).

Table 1
Set of questions used in the interview guide.

Themes	Questions
Demographic Information	● Age, education, occupation, etc.
Usage	● Usage condition
	● How did you set the Autopilot?
Secondary task and vigilance	● Did you perform a secondary task while using Autopilot? Why?
	● What kind of secondary task did you perform?
	● How long did you spend on your secondary task each time your eyes were off the road?
	● When you used Autopilot, did you feel bored? When you used Autopilot, did you feel your attention wandering?
	● If you felt bored, what did you do?
	● Did the vehicle alert you to put your hands on the wheel when you used Autopilot?
	● Did you feel it was wrong to perform the secondary task while driving?
	● What did you do to ensure safety while you were performing the secondary task?
	● Did you ever have an accident while you were using Autopilot? If yes, describe the accident.
Mental model	● How did you learn to use the Autopilot?
	● Did you ever experience any 'bug' in the Autopilot?
	● In general, when and where did you take over control of the vehicle?
	● Did you read the user manual?
	● Do you think it is necessary to train drivers to use the Autopilot?
Trust	● Do you trust this Autopilot? Why or why not?
BA process	•Did using the Autopilot influence your manual driving? If so, how?
	● Was there any change in how you use Autopilot now compared with how you used Autopilot the first time? If so, what changes do you see?
	● How long did it take you to feel comfortable using Autopilot?
Suggestion	● Please share any suggestions regarding the autonomous vehicle.

experience usually increases self-reported trust in automation through learning the reliability and predictability of the system (Rudin-Brown and Parker, 2004; Gold et al., 2015; Walker et al., 2016). However, excessive trust in the capabilities of assistive technology can lead to engagement in secondary tasks while driving (Rudin-Brown and Parker, 2004).

1.4. Research questions

Compared with older vehicle technology, a PAS can assist drivers with both lateral and longitudinal control, and provide more automatic functions to drivers. The interaction between the driver and PAS probably generates new BAs and may cause new safety issues. Thus, the BAs induced by this new PAS and the underlying cognitive processes related to these BAs are worthy of investigation.

A previous study of vehicle technology indicated that BA should be considered in three stages: immediate, short term, and long term (Manser et al., 2013). Immediate refers to adaptation that may occur soon after a driver experiences a change in a safety system, and the PAS studies conducted in experimental settings can be categorized according to this stage (Manser et al., 2013). Short-term adaptation is typically characterized by a significant but lower rate of behavioural change for drivers, where the adaptation may be characterized by gradual changes in drivers (Manser et al., 2013). Considering that it would take two weeks for drivers to learn how to use an ACC based on experience (Viti et al., 2008) and that the understanding and BA of the driver of a Tesla PAS would alter over time in the first six months (Endsley, 2017), we focused mainly on the short-term usage of a PAS where the experience of drivers varied from one to five months.

Previous research has demonstrated that PAS drivers exhibit decreased vigilance, such as increased mind wandering and less frequent eye blinks (Körber et al., 2015). In a study based on a critical situation, when PAS drivers were monitoring the road without performing a secondary task in a simulator, 2 s appeared to be insufficient for them to take over control (Mok et al., 2015). A driving simulator study also indicated that the driving performance degraded when the level of automation increased (Strand et al., 2014). Moreover, an on-road experiment showed that a PAS could increase the engagement of drivers in secondary tasks but the participants could adjust their level of engagement according to the driving velocity (Naujoks et al., 2016). Vehicle automation can reduce the self-reported workload and improve situation awareness, but the engagement of drivers in secondary tasks may decrease their actual situation awareness (de Winter et al., 2014). However, laboratory simulation studies have focused mainly on immediate BA, and thus their effectiveness was limited in terms of characterizing the short-term effects on BA.

Two recent studies have considered the experiences of drivers with respect to PAS. The first was a questionnaire study that focused mainly on the experience and attitude of Tesla Autopilot drivers towards automation failures (Dikmen and Burns, 2016). The other was a naturalistic driving study based on the author's own driving experience, including assessments of situation awareness and problems with autonomy (Endsley, 2017). In contrast to these previous studies, we considered the BA of PAS drivers based on a systematic framework.

Hence, the aim of this study was to explore the BA of early PAS adopters, especially their short-term BA, by obtaining information based on the self-reported behaviour and understanding of drivers. According to the framework of the '*qualitative model of behavioural adaptation*' (Rudin-Brown, 2010), we focused on changes in BA, trust, and mental models over time in drivers, where we addressed the following research questions.

- Q1: What are drivers' short-term BAs when using the PAS?
- Q2: What are drivers' short-term mental models of the PAS?
- Q3: What are short-term levels of trust in PAS among drivers?
- Q4: What are the differences in these three areas in terms of immediate and short-term usage?

2. Method

Considering the limited number of early PAS adopters, we conducted in-depth semi-structured interviews to explore the individual experiences and understanding of PAS. This method is valid and reliable for obtaining knowledge about general driving behaviour, attitudes towards new technology, mental models, and trust among drivers (Cherri et al., 2004; Kazi et al., 2007; Beggiato, 2014).

The structure of the interview was based on the '*qualitative model of behaviour adaptation*' (Rudin-Brown, 2010; see Fig. 1). The interview comprised four parts extracted from this model: trust, mental model, driving task (secondary task engagement and vigilance decline), and system (usage). In addition, two other categories comprising 'BA process' and 'suggestion' were considered in order to explore the changes in the former concepts over time and expectations regarding the development of PAS among drivers. Thus, a semi-structured interview format was used and a set of open-ended questions was developed based on these main themes (see Table 1).

In total, 20 owners and drivers of Tesla vehicles with Autopilot (the PAS function; version 7.0 or 7.1) were recruited using the snowball technique (Atkinson and Flint, 2001). The Autopilot had typical PAS features: ACC, lane-keeping system, and automatic lane-changing system. The PAS also had a hands-on-wheel warning system that displayed a “Hold steering wheel” message on the instrument panel and it eventually sounded a chime if it did not detect the driver's hands on the steering wheel. In addition, if the driver did not respond to the warning, the vehicle started decelerating and stopped gradually (Tesla, 2016, 2015). Initial contacts were made through informal networks via a post placed on the Chinese Forum of Tesla owners, which also allowed other contacts to be made with owners. Data were collected in the first half of 2016. Interviews were conducted individually and they typically lasted at least 1 h. Participants were reimbursed with 100 RMB for attending the interview. The interview was conducted over Voice chat via WeChat (an instant messaging application in China) or a telephone call. Before each interview, the participant was informed about the purpose of the interview and their confidentiality (Shenton, 2004). The semi-structured interview was then conducted using the sample questions. However, the questions were not limited to those in Table 1 and the participants were encouraged to provide more descriptive details and to be frank from the outset of each section. The whole interview was audio-recorded with the participant's consent.

All of the interviews were carefully transcribed verbatim. Next, the participants were invited to review and amend the material. The transcripts were analyzed using a computerized version of the long-table approach (see Herriot et al., 2008; Garip and Yardley, 2011). In this study, the original transcripts were first categorized according to the corresponding question using Excel. Subsequently, the category system was reviewed and discussed in order to transfer some sentences to a more fitting theme, and the initial ideas for themes were derived and refined based on preliminary indicators in the data. The results for each category are reported in the following section, and the frequencies of some themes are also calculated and presented.

3. Results

3.1. Demographics of participants

Most of the Tesla owners had a university education (85%) and all of them lived in cities in China. The Autopilot function was released in October 2015 in China and all of them had experienced it for more than one month (see Table 2). All of the participants had a positive attitude towards Tesla and they treated their identity as Tesla owners as a honour by sharing the experience positively. All of the participants had joined several online communities (WeChat groups) that might develop into offline ones, through which they expanded their social networks.

Table 2
Demographic information for the driver participants.

Item	N	%
Gender		
Male	18	90
Female	2	10
Age	36.7(M)	5.2(S.D.)
Education level		
High school	1	5
Junior college	2	10
Bachelor degree or above	17	85
Occupation		
Manager	15	75
Engineer	4	20
Public employee	1	5
Driving experience (years)		
< 2	1	5
2–5	3	15
5–10	2	10
> 10	14	70
Autopilot experience (months)		
1–3	16	80
> 3	4	20
Autopilot usage version		
7.0	18	90
7.1	2	10
Annual driving distance (thousand kilometres)		
< 20	1	5
20–30	3	15
30–50	9	45
> 50	7	35
City of residence		
Beijing	2	10
Shenzhen	10	50
Wenzhou	2	10
Zhongshan	1	5
Hongkong	2	10
Zhuhai	3	15

3.2. Usage

All of the participants had a positive attitude towards the Autopilot and reported that their user experience was better than that with any other driving system with a single driver assistance feature (ACC, cruise control system, and lane departure warning system) they had encountered previously. They reported some ‘appropriate’ use conditions. The majority (95%) of the participants reported that Autopilot could be used effectively on motorways and city limited-access expressways. Bicycles and pedestrians are excluded from these roads. Five drivers (25%) mentioned that they felt less anxious when using the PAS and they avoided their tendency to change lanes in order to overtake slower traffic, although their journey would take longer. In addition, it was more convenient for them to engage in secondary tasks than without the PAS. Only one female participant claimed that she avoided using it on the motorway because the high speed without control frightened her. Eight (40%) drivers reported that they preferred to drive in the leftmost lane, which is the passing lane under Chinese traffic regulations, and they usually experienced less cut-in situations (in China, driving in the leftmost lane does not require the highest speed because more lane-changing behaviours and taking more opportunities to move forward can help to arrive sooner at the destination). In general, the drivers found that the system was more useful and reliable in low and stable traffic on motorways, and they preferred to activate it on familiar roads.

Most of the participants (95%) also reported that the PAS was quite helpful with traffic jams on urban roads because the annoying repeated ‘stop and go’ pattern could be handled by the system, and Autopilot made them feel less anxious and frustrated when encountering congestion. The participants had some concerns about the tendency of other drivers to overtake and cut in when using PAS in high-density traffic. One participant with driving experience in the USA complained that: ‘If the driving environment in China was as good as that in the USA, Autopilot would be more useful while driving in traffic jams. At present, I have to be very cautious and check whether there a vehicle is cutting in ahead’. In some cases, this led to harsh braking and the activation of the collision warning system. For this reason, the drivers preferred to set a shorter headway distance on urban roads than on the motorway so there would be no room for other vehicles to cut in. In general, most drivers (95%) reported that the PAS was not useful on other types of urban road because the traffic was too complex.

According to the Tesla Model S owner's manual (Tesla, 2015, 2016), use in traffic jams and bad weather conditions constitutes a violation of the rules (see Table 3), but none of the participants regarded this as a violation of the rules. Most participants (85%) said that they avoided using the PAS in bad weather conditions, although the information on the dashboard showed that the system could be activated. Only two

Table 3
Usage conditions for PAS drivers and violations of the user manual.

Driving condition	Autopilot use (Yes/No) (No.)	Preferred condition	Violation (Yes/No)	Evidence	Motivation
Motorway	Yes (19)	Fastest lane	No	' … it was quite useful on the motorway. We can just transfer the authority for driving to the car and happily observe its perfect work'. 'Once I get on the motorway, I will use the autopilot if I am not in a hurry'. 'Once I was very sleepy on the motorway and I used Autopilot. It saved my life. It seems like Autopilot is the backup for the driver'.	Less effort Less anxiety Secondary task engagement
Local loop	No (1)		No	'The speed of all the drivers is so fast I am too frightened to activate it'.	Fear
	Yes (2 in Beijing with local loop)	Fastest lane	No	'I'll use the system while commuting if time is not limited'.	Less effort Less anxiety Secondary task engagement
Urban road	Yes (19)	Mainly Traffic jam	Yes	'Repeated use of the brake and accelerator pedal were replaced by using the system'.	Less effort Less anxiety
	No (1)		No	'I don't like to use it on the urban road. There are too many obstacles and it is not as useful'.	Less usability
Bad weather conditions	Yes (fog = 1; rain = 2)		Yes	'The system can "see" better than my eyes'. 'I just did a test and found that the system could be activated so I felt safer than during manual driving'.	Feel safer
	No (17)		No	'I am too frightened to try. Maybe it cannot be activated'.	Fear

participants (10%) had used the system in heavy rain and one in heavy fog because they thought that the Autopilot could 'see' better than their own eyes.

3.3. Secondary task engagement and vigilance

The manufacturer requests that Tesla owners keep their hands on the wheel in order to avoid abuse of the Autopilot and to ensure that they can take over immediately in critical situations (Tesla, 2015, 2016). The instructions in the manual indicate that 'Autosteer (the longitudinal control function in Autopilot) is a hands-on feature. You must keep your hands on the steering wheel at all times' (Tesla, 2015, 2016). However, reports of engaging in potentially distracting activities were highly prevalent with PAS. Eighteen of the 20 participants acknowledged that they engaged in at least one type of secondary task that involved taking one or both hands off the steering wheel while in the automated mode (see Table 4 for details). All of the participants knew that engaging in a secondary task was contrary to the instructions and most (65%) of them hesitated for a while before answering the relevant question. In addition, some of the drivers (30%) answered this question by starting with the word 'Frankly' or 'To tell you the truth', which indicated that they had been aware that secondary task engagement was not appropriate while using PAS.

The reported duration associated with secondary task engagement when the eyes were off the road was usually 3 s–5 s. However, the time when the eyes were off the road was reportedly even longer on familiar motorways. One participant said that: 'Once I spent almost half an hour playing on my mobile phone without looking up to check the road conditions'. Six participants (30%) claimed that they might keep one hand on the steering wheel and position the other hand with a mobile phone between their eyes and the steering wheel. They thought that they could easily monitor the road conditions by using peripheral vision in this posture. Three participants (15%) reported that they only performed secondary tasks on familiar roads. In addition, many participants (40%) used the word 'prediction' and mentioned that they could predict the traffic conditions over the next several seconds, and then look at their mobile phones.

The hands-on-wheel warning system did not always prevent secondary task engagement by drivers because some (45%) preferred to put one hand on the wheel while using their mobile phone. One participant mentioned that: 'Once the chime goes off, I'll put one of my hands on the wheel and shake the wheel slightly until the alarm stops'.

Seven participants (35%) acknowledged that they experienced boredom or that their vigilance declined when using the PAS. One of them attempted to sing songs in order to keep himself alert. The others (65%) reported they had never experienced boredom because they thought that playing with their mobile phone could help them keep awake. One participant reported a specific case where he had once been too drowsy to keep his eyes open on the motorway before using Autopilot. He then activated Autopilot, which helped him to arrive home safely. He indicated that Autopilot was not the cause of decreased vigilance, but instead it could be regarded as the solution.

3.4. Mental model

Drivers' PAS mental models involve the actions and environmental events that influence the PAS function, which the drivers can then employ to decide when and where to activate or deactivate the PAS. The characteristics of the PAS mental models were reflected by the participants' understanding of the functional limitations of PAS and how they decided to take over control (see Table 6).

Based on the correct mental models, drivers could make successful predictions of the PAS action and the road environment. In addition to the functional limitations in the PAS mental models, other environmental events might cause drivers to selectively take over control due to their prediction for risks, such as the appearance of a police officer,

Table 4
Secondary task categories for PAS drivers.

Secondary task	Numbers of participants (out of 20)	Evidence
Wechat voice chatting	18	'To tell you the truth, I use Wechat during manual driving but I cannot use it as frequently as when I drive with Autopilot. The Autopilot gives me more time to talk via Wechat on my phone'.
Wechat text chatting	6	'I cannot text on Wechat during manual driving. Now I can text while using Autopilot'.
Playing phone games	3	'As soon as I use Autopilot, I play on my phone. Having nothing to do is so boring. To tell you the truth, I sometimes play mobile games'.
Eating or drinking	4	'Before using Autopilot, I would never drink water on the road. Now I can because my eyes are only off the road for several seconds'.
Applying make-up	2	'Sometimes I can put on lipstick or do some touch-ups'.
Taking photos	2	'While using Autopilot, I have to admit I take selfies'.
Editing photos	1	'You know as girls, sometimes there's a need to edit photos. Autopilot can help me and then I can do it while driving'.
Singing songs	1	'I am too scared to do other things. Having nothing to do is a little boring, so I sing songs. You see I can still keep my hands on the wheel'.
Voice notes	1	'On the local loop, I even could "write" blog posts with the help of voice notes. It helped save me a lot of time'.

Table 5
Trust in PAS by drivers in specific situations.

Trust (Yes/No)	No. of participants (out of 20)	Reason	Evidence
Yes	19	Reliability of technology	'Nothing serious has happened yet. Everything it does never surprises me. It is trustworthy'.
		Brand of vehicle manufacturer	'I am a fan of Musk (Tesla CEO). As long as he is not afraid to sell Autopilot to customers, I am not afraid to trust it'.
		Traffic safety authorities	'I think the company should be approved to sell the vehicle by a 'possible' traffic safety department. You know, Autopilot was once forbidden in Hong Kong. Some department should be in charge of the quality of the vehicle for sale'.
No	1	External knowledge	'I am an IT programmer. I am very clear about the reliability of the software. I am afraid to trust it. I am more reliable myself'.

the presence of trucks, a sudden increase in traffic density, a sudden decrease in traffic velocity, or a parked vehicle in the other lane. These triggers shared the same characteristic that it was not necessary for drivers to take over control in these situations, but the situations could potentially develop into a critical situation. In general, drivers had to take over control from the PAS in a limited period of time when faced with function limitations, and they also selectively took over control from the PAS when they could predict that the presence of function limitations was highly likely in the near future.

The PAS mental models of the participants were formed using different information sources, such as news on the Internet, information shared with other vehicle owners, the manual for the system, some guidelines from the salesperson, and the actual practices of the drivers (see Table 7). The user manual stated that the list of limitations was not exhaustive and it was the driver's responsibility to remain in control at all times. This confused one participant who performed an experiment based on clearing various obstacles, including a bicycle, motorcycle, and dustbin, in order to test whether a moving or stationary target could be recognized by the Autopilot. He even wrote a blog to share the results with other Tesla owners. Moreover, several participants (35%) reported that the introduction given by the salesperson confused them because the salesperson first emphasized that the Autopilot is a self-driving function, whereas the official website described it as aided driving, which made it harder for them to understand its functions, especially before they experienced the functionality for themselves. Most of the participants (60%) thought that the training offered by the instructor or salesperson was useless. One participant said that: 'It feels like the first smartphone I bought. I did not listen to the salesperson's introduction or even read the user manual. I just tried to use it and eventually worked out how'.

After practicing, the mental models of PAS formed by the drivers were updated via interactions with the external environment, especially by encountering objective functional limitations. If it was a 'first encounter', the participants were often very frightened. One of the participants described how he reacted the first time he encountered a functional limitation induced by a T-junction: 'When I drove into the T-junction, the radar suddenly lost contact with the vehicle in front and the system did not remind me to take over and it suddenly accelerated, which scared me a lot. I felt very nervous and turned the wheel sharply to take over the car'.

Another factor to consider with respect to mental models of PAS is that the objective existing functional limitations changed because the system had a 'learning' function and it was also upgraded once within 3 months. Almost all of the participants reported no perception of the

Table 6
Samples of statements illustrating the limitations of the PAS experienced by drivers.

Limitations reported	Evidence
T-junction	'The radar lost contact with the vehicle in front suddenly and the system did not remind me to take over, but the car suddenly accelerated'.
Fuzzy lane lines	'If there was no car in front, the Autopilot could not recognize the lane lines. Once the lines became fuzzy, I had to take over'.
Road cones	'It could not recognize the road cones. I had heard that the upgraded system could recognize them, but I was too frightened to try it on the motorway'.
Fences	'I think it sometimes fails to recognize the type of white fence that is a characteristic of the roads in China'.
Being overtaken	'When others cut into my lane, my car would brake sharply'.
Vehicle in front braking or starting sharply	'If the front car brakes or starts sharply, my car sometimes reacted too sharply'.
Driving on the curve	'If one line became dotted on the curve, the car went straight at the same speed'.

Table 7
Samples of statements illustrating the formation of mental models of PAS by drivers.

Source of mental model	No. of participants (out of 20)	Evidence
News on the Internet	15	'There is a lot of information on the Internet. I just read it and learned about the Autopilot'.
Other owners	7	'Tesla owners share in the same Wechat group and we might discuss the Autopilot. If somebody comes across a dangerous situation, all of us will try to avoid that situation'.
User manual	5	'I read the manual and learned about some limitations, but the manual does not cover all the dangerous situations so I had to remain cautious on the road'.
Salesperson	2	'I do not look at the road as many times as before. I focus my attention on the display because the salesman told me that it can show me how the Autopilot works'.
Experiment	1	'I did not know what obstacles it could recognize, so I performed several experiments to test it. I also wrote a blog and posted it on the Internet'.
Personal practice	20	'During the first two weeks, I just watched as carefully as possible to learn how the system would behave'.

Table 8
Differences between immediate usage and short-term usage.

Theme	Immediate usage (< 2 weeks)	Short-term usage (> 2 weeks)	Evidence
Mental model	Mainly knowledge-based	Mainly experience-based	'Mostly, other Tesla owners offered me some advice before using it and warned me about some dangerous situations. After I bought it, I found that it was not as good as other owners commented but not as bad as news reported in the news'.
Trust level	Low	High	'At first, it made me very scared. It felt like my wife was driving the car and I was sat in the co-pilot's seat. I then tried to use the Autopilot on an empty road for a while. After about two weeks, I could fully trust the Autopilot'.
Secondary task engagement	Less	More	'At first, I dared not do other things. After a while, I found that the Autopilot worked very well. I then began to play on my phone'.

learning ability of the Autopilot, but one participant said that: 'I found that the automated mode suddenly began to recognize the lane, which it had not recognized before'. Another participant tried to take over repeatedly even when it was not necessary because he believed that this behaviour could help the system to learn his intentions. In general, all the participants knew some aspects of the system's functional limitations. These were only perceived as annoying because it was clear that the participants tolerated the limitations, possibly because they were easy to learn and they never caused serious accidents.

The only crash mentioned by one participant was closely related to his inaccurate mental model of PAS. He said that: 'At first, I was using the Autopilot and there was a taxi overtaking, which made me come to a complete halt. I found one-third of the body of the taxi cutting into my lane. I thought the Autopilot could recognize it as the 'vehicle ahead', so I subsequently re-activated the Autopilot and began to play on my phone but the system accelerated suddenly, which I felt. When I looked up it was too late. It had run into the taxi'. In this driver's mental model, the PAS should have recognized the cutting in taxi and followed it, but in reality, the PAS did not recognize the taxi and it continued to follow the previous front vehicle. Moreover, the driver's engagement in a secondary task made the situation even more dangerous.

3.5. Trust

In general, the perceived trust of the participants in the automated mode appeared to be fairly high (see Table 5). Only one participant said that he did not trust Autopilot because he was a former IT practitioner and he was acutely aware that Autopilot was a piece of software so it must contain bugs like all other software. Compared with Autopilot, he reported that he trusted himself more. The other participants explained why they trusted Autopilot, where this trust was mainly attributed to the reliability of technology, the vehicle manufacturer's brand, and traffic safety authorities. They considered that before a PAS can be introduced onto the market, the reliability of the system must be guaranteed by a traffic safety department.

3.6. Behavioural adaptation

In this section of the interview, we focused mainly on changes in the previously discussed areas over time. According to the participants, usage for 30 h or two weeks was generally required to become familiar with the system, which is consistent with the findings of previous studies of ACC users. In a FOT conducted in the Netherlands, the results showed that 67% of the drivers learned how and when to use an ACC, as well as when to overrule it, within two weeks (Viti et al., 2008).

As mentioned in the previous section, the initial mental models of the PAS were knowledge based, but drivers still felt nervous when they began to use it because they were not sure whether the vehicle would behave as expected. After cautious interactions with the Autopilot, they learned and confirmed how the vehicle would behave in different conditions, while their trust level also increased and they gradually began to engage in secondary tasks (see Table 8).

A carry-over effect was reported among the participants. Some participants (15%) reported that they felt a little uncomfortable if they drove a conventional vehicle. One participant said that: 'Almost as soon as I drive onto the motorway, I activate this mode. The only thing that concerns me is that I am relying more on this system and one day I will not be able to drive as well as before'. The participants also indicated that it was harder to drive without the system after driving the car in automated mode for some time. One participant said that: 'If it is said that my driving ability is declining, of course I will deny it. However, if it is said that I do not feel as comfortable in conventional cars as before, I have to admit it'. Furthermore, enjoying the control of steering was mentioned by one participant who said that: 'I really enjoy the automation that the car offers, but I still enjoy driving it myself. If one day the vehicle is fully automated, I'll not be eager to buy it'.

3.7. Suggestions

The participants provided further suggestions regarding the design of the PAS (Table 9). These suggestions indicate the expectations of drivers with respect to the technological development of PAS and might be suggestive of challenges related to the formation of accurate PAS mental models.

Table 9
Suggestions for the design of the PAS.

Item	No. of participants (out of 20)	Description
Augmented virtual reality head-up display	2	A display could provide information about the PAS's current status and future actions, thereby improving the driver's understanding of the automated actions.
Driver monitor system (Rudin-Brown, 2010)	2	For monitoring the driver's attention and vigilance state, and bringing the driver back in the loop as required.
A signal outside a PAS-active vehicle	5	To remind other road users that an autonomous vehicle is being driven by a PAS rather than a human driver, thereby reminding other road users to keep a safe distance.

4. Discussion

4.1. Q1: What are drivers' short-term BAs when using the PAS?

The results indicated that after short-term usage, the drivers learned when and where to use the PAS in an appropriate manner. In general, they preferred to use the PAS on motorways, city loops, and traffic jam conditions on urban roads in good weather environment, especially on familiar roads where they found the PAS more useful. While using the PAS, the participants universally engaged in secondary tasks and the hands-on-wheel warning system could not always bring the drivers back into the loop. The universality of performing secondary tasks in this study contradicted the results obtained in a previous questionnaire-based investigation in Canada, which indicated that Tesla drivers tended not to engage in secondary tasks while using the Autopilot (Dikmen and Burns, 2016). This previous questionnaire study required that the participants described their driving behaviour and results, but secondary tasks were not mentioned. By contrast, our study focused on secondary task engagement in several questions.

The average duration of eye glances away from the road reported by the PAS drivers was from 3 s to 5 s per occurrence. A previous road experiment showed that after driving with a PAS for around 2 h, most glances away from the road lasted ≤ 3 s in situations where the drivers were engaged in a secondary task on motorways (Salinger, 2012). Considering the limited experience allowed in the previous study, the average duration of 3 s–5 s in the present study is reasonable, although further evidence needs to be collected in naturalistic PAS studies. According to naturalistic manual driving studies, glancing away from the forward roadway to perform secondary tasks increases the likelihood of crashes and near-crashes. The risk is greater when the duration of glancing away from the road is longer (Klauer et al., 2006; Simons-Morton et al., 2014). Glancing for more than 2 s for any purpose increases the near-crash/crash risk (Klauer et al., 2006). During the single crash mentioned in this study, the PAS driver was using a mobile phone, which prevented him from reacting in a timely manner before the crash. The fatal accident investigation involving a Tesla reported by the NHTSA (2017) indicated that intervention should have been made by the driver at least 7 s before the crash. The distraction of PAS drivers is a high risk to road safety.

Over a long period with many interactions, the PAS drivers gradually learned to use the system in relatively safe and smooth conditions, where monitoring the road did not occupy much of the driver's cognitive resources and frequent input from the driver was not necessary to moderate PAS behaviour. Thus, the experience of PAS could increase the subjective feeling of safety for drivers and reduce their workload (de Winter et al., 2014; Naujoks et al., 2016; Sibi et al., 2016). According to the Risk Homeostasis Theory and Task Difficulty Homeostasis Theory, drivers have individual target levels for risk and target levels for task difficulty (Wilde, 1982; Fuller, 2005). Thus, using PAS in these conditions would reduce the perceived risk level and perceived task difficulty to below the target levels, whereas secondary task engagement could increase them. Seven participants (35%) acknowledged that they felt bored or that their vigilance declined when using the PAS. The other participants reported that they never experienced boredom because they used the secondary task as a countermeasure to prevent decreased vigilance, which is consistent with the findings of Endsley (2017), who showed that in order to relieve the boredom and decreased vigilance, it was beneficial to switch attention to competing tasks, such as daydreaming, adjusting the navigation system and sound system, or attending to text messages. However, the PAS drivers in the present study did not consider that they suffered from low situation awareness under automation due to complacency, reduced engagement, and decreased vigilance, as also shown in another study of an automated system (Kaber and Endsley, 2004).

In addition, in circumstances where the traffic was steady and predictable, the drivers had to immediately take over control from the PAS when they faced a latent hazard, such as a sudden increase in the traffic density or the presence of several trucks. Latent hazards are possible roadway threats that do not necessarily develop into hazards that require immediate action (Vlakveld et al., 2011). Thus, it is very likely that glancing away from the road for 3 s–5 s will not make the PAS drivers miss a latent hazard. In general, manual control is preferred to automation in this particular context. Secondary task engagement by PAS drivers would have decreased their situation awareness (de Winter et al., 2014) but the relatively short duration of glancing away from the road and the drivers' positive intervention to the PAS when facing the latent hazards could protect them from exposure to extremely dangerous situations to a certain extent. Gibson et al. (2016) proposed using attention to latent hazards as a measure of the engagement in the driving task and secondary task engagement to measure the disengagement from the driving task in highly automated vehicles (the automated system can monitor the road instead of the driver and alert the driver to take over control in critical situations (SAE, 2014)). The PAS drivers' positive response to a latent hazard reflects a safety margin mechanism. The 'safety margin' refers to a distance in time or space maintained by road users in order to avoid high-risk situations (Kulmala and Rämä, 2013), which has been developed into actual time-based safety margins parameters such as the *time-to-collision* (Summala, 2007). In manual driving, the vehicle is under the driver's control, whereas the vehicle is manipulated by the PAS in partially automated vehicle driving. The ability of the PAS to recognize an object and make a reaction determines the *time-to-collision*. Thus, the current driving state of the subject vehicle, the distance to other objects, and the driver's understanding of the function of the PAS can influence the perceived *time-to-collision*. The safety margin in PAS driving appears to be more complicated than that in manual driving, where it acts as a threshold to protect the driver from exposure to critically dangerous situations.

In previous PAS simulation studies of secondary task effects, the drivers were mainly forced to use the PAS and a mandatory system-paced secondary task was performed (de Winter et al., 2014; Naujoks et al., 2016). However, on real roads, drivers usually exhibit self-regulatory behaviour strategically and tactically because they are free to decide when to activate the PAS or to work on a secondary task mainly according to the demands of driving. In manual driving, the self-regulatory behaviour of drivers is mainly reflected by their control of the driving speed and steering (Young and Michael, 2008). However, in automated driving, the drivers do not need to control the vehicle to the same extent. Thus, the decisions made by drivers about when to activate or deactivate the PAS, as well as when to shift their attention between the road and a secondary task, play important roles in the development of BA. In a previous Tesla study, the author generally conducted secondary tasks only in situations where the automation was highly reliable (Endsley, 2017). In the present study, the hands-on-wheel warning system could not actually bring drivers back into the loop, which indicates that the PAS drivers had a primary control over the risk level. In the previous Tesla study, the steering wheel did not have a pressure sensor but instead it reacted to left-right steering inputs, and it was poor at detecting the driver's hands (Endsley, 2017). Thus, further designs of the human–machine interface should consider secondary task engagement by drivers by improving the system algorithms and related settings in order to help drivers maintain an appropriate level of risk.

4.2. Q2: What are drivers' short-term mental models of the PAS?

In the '*qualitative model of behavioural adaptation*' (Rudin-Brown, 2010), a driver's mental model of the driving task is an important element that directly influences their behaviour as well as the likelihood and nature of any BA (Rudin-Brown, 2010). Drivers' mental models of the driving task when using the PAS are formed based on their mental models of the PAS and the mental models of the road environment. The mental models of the PAS should reflect how they understand the functionality of the PAS. In general, there should be three parts to a PAS driver's mental model: appropriate conditions for use, such as motorways; latent hazard triggers, such as a sudden increase in traffic density; and functional limitations, such as the inability of the system to recognize a traffic cone.

In manual driving, drivers mainly need to understand the environment, and their mental model of the driving environment may be reflected in their situation awareness, such as the current driving conditions and the locations of other road users (Strayer and Fisher, 2016). However, in PAS driving, the drivers need to understand the functionality of the PAS as well as the environment. Furthermore, the functionality of the PAS even determines what drivers need to know about the environment. For example, in the absence of a preceding vehicle, the PAS must recognize the lane markings in order to plan the navigated route. The driver has to take over control when the markings become fuzzy. Thus, the function of the PAS determines whether drivers need to pay greater attention to the lane markings. In conclusion, in PAS driving, drivers need to understand the environment but also the functionality of the PAS. These two factors contribute to a driver's comprehension of the overall PAS–environment system.

When the PAS drivers began to use the system, they usually had relatively incorrect mental models, such as incorrect expectations regarding the effectiveness of PAS at T-junctions. At this stage, they might have possessed unrealistic expectations about PAS because one of the participants mentioned that he felt very nervous when he encountered the functional limitation induced by a T-junction for the first time. Endsley (2017) also found that it took numerous attempts by trial and error to understand how to use a PAS. However, after a learning phase of approximately two weeks, the PAS drivers in the present study began to engage in secondary tasks due to their better understanding of the functionalities of the PAS, but their incorrect mental models combined with low situation awareness would result in an increased accident risk. In the crash experienced by the participant in this study, the driver switched his attention to the phone and expected that the PAS would recognize the taxi cutting in as the 'vehicle ahead' but it did not. This difference between expectation and reality increased the risk of an accident by making it more likely that the driver would react slowly in any overtaking situation. Manufacturers are responsible for helping drivers to establish an accurate mental model of their PAS.

4.3. Q3: What are short-term levels of trust in PAS among drivers?

Levels of trust in the PAS were relatively high according to the participants because most of them considered that the introduction of the system onto the market implied that the system's reliability had been guaranteed by the vehicle manufacturer and traffic safety authorities. In fact, based on the reports of secondary task engagement by drivers, we may conclude that the drivers trusted the system excessively.

Several factors might have contributed to this problem. Trust is often seen as a by-product of the perceived accuracy of a mental model (Beggiato and Krems, 2013), and it could help PAS drivers to identify relatively safe and appropriate driving conditions. The state of the traffic could usually be anticipated by the PAS drivers, so they would have actively taken over control when they predicted a risk. Under safer conditions, the reliability of the PAS was fairly high and no serious accidents were reported by the participants. Moreover, all of the participants in this study were Tesla owners and early adopters of this technology. They shared certain distinct characteristics, where they enjoyed using the latest technology and had a greater likelihood of trusting automated systems. In additionally, they were loyal to the Tesla brand and they trusted this company.

4.4. Q4: What are the differences in these three areas in terms of immediate and short-term usage?

According to the participants, they required a period of approximately 30 h or two weeks to become familiar with the PAS. Thus, the short-term BAs, such as secondary task engagement, were generated mainly after a usage period longer than two weeks. At the same time, they built more accurate mental models and higher levels of trust compared with those after immediate usage. In the previous Tesla study, the author also reported increases in satisfaction, usefulness, trust, and situation awareness over six months (Endsley, 2017). Based on their more accurate mental models and higher level of trust, drivers would engage more in secondary tasks compared with that after immediate usage. While conducting the secondary task, the PAS drivers had a tendency to place one hand on the wheel to avoid a warning from the hands-on-wheel warning system.

The results obtained in this study indicate that pre-existing knowledge mainly influenced the mental models, trust, and behaviour of drivers during the immediate usage stage, whereas experience of use played the most important role in the short term. According to Rasmussen's framework (Rasmussen, 1987), task performance can be distinguished into three levels: knowledge-based, rule-based and skill-based. Thus, in the immediate BA stage, PAS drivers often exhibited rule-based and knowledge-based behaviour, whereas in the short term, deciding whether to use the PAS mainly involved rule-based behaviour and the set of rules increased in size with more experience over time.

In general, according to the participants in this study, the overall process of adaptation to using the PAS can also be regarded as a process of risk homeostasis. As the drivers learned more about the functions of the PAS, they became increasingly aware of the safer conditions for its use, which reduced their workload and perceived risk. In addition, they gradually engaged increasingly in secondary tasks, which increased the workload and perceived risk for the drivers. Secondary task engagement could increase the perceived risk for PAS drivers and knowing the safer use conditions where the PAS was relatively reliable could mitigate the risk to a certain extent.

4.5. Safety-related implications

The Autopilot user manual demands the constant attention of the driver to the vehicle; however, the opportunity to engage in secondary tasks (which was not prohibited by the hands-on-wheel warning system) was widely exploited by participants in this study. Moreover, no other in-vehicle system can detect the driver's lack of attention to the road and force them to maintain their attention. Thus, these PAS drivers have a high potential risk of accidents. Furthermore, the unsafe use of the system during bad weather conditions is encouraged by the interface design because the interface shows that the PAS can be active, which is a violation of the Tesla user manual (Tesla, 2015, 2016). Only 25% of the PAS drivers in this study reported that they had read the manual carefully. In addition, during the periods of use, the PAS drivers mainly learned the functions based on their own experience, which also required more attention. In a previous Tesla study, the author also reported that they had to rely on trial and error to determine how the PAS would work in different driving conditions (Endsley, 2017).

In the present study, the PAS drivers reported one crash, where the driver was using a mobile phone and had an incorrect expectation of the action that would be taken by the PAS. In the future, the PAS should aim to learn more about the driver's state (attention, vigilance, and understanding of the functions of the PAS) and give appropriate warnings to engage them, such as by installing an effective driver monitoring system (Rudin-Brown, 2010).

5. Conclusion

In this study, we examined the current state of partial automated driving in the real world and explored the BAs of drivers with respect to the PAS. Our interview data showed that these early PAS adopters had a very positive attitude towards the system and their trust in it was considerably high. After usage for two weeks, the drivers usually had an accurate mental model, which they could employ to identify relatively safe usage conditions. In these conditions, the drivers universally engaged in secondary tasks. In addition, they exhibited some self-regulatory countermeasures such as how to select safe usage conditions and a safety margin maintained by themselves to avoid exposure to excessively risky situations. The main contributions of this study are insights into the real-world use of a PAS during the early stages of adoption.

6. Study limitations

Given that our study employed an interview methodology, we recognize that response and sampling biases were present. Surveys are based on self-reported information and although the insights gained into the perceptions of participants are invaluable, differences between the stated and revealed preferences were probably not captured in this study. Another limitation of the study is that the sample might not have been representative of PAS drivers because the sample size was low and Tesla owners are a special group with unique characteristics. The participants tended to be wealthy and obtained more enjoyment from technology than the general population of drivers. In addition, they were loyal to the Tesla brand and they trusted this company greatly. Their experiences with and attitudes towards this technology might not be the same as those of the general driving population. In addition, the participants were all Chinese drivers. They generally lacked a correct understanding of the importance of practical guidelines regarding safe driving, but instead they placed more trust more in their driving skills, experience, capability, and physical condition (Zhang et al., 2006). Moreover, the participants were active in online communities. A previous study demonstrated that these online community members share a higher level of extraversion, conscientiousness, narcissism, and self-disclosure (Sun et al., 2014). Thus, we advise caution with respect to generalizing the results of this study.

Declarations of interest

None.

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