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Designing for Comfort in Shared and Automated Vehicles (SAV): a Conceptual Framework

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Abstract To date, automotive design and research is heavily biased towards the driver. However, with the rapid advance of vehicle automation, the driving task will increasingly being taken over by a machine. Automation by itself, however, will not be able to tackle the transport challenges we are facing and the need for shared mobility is now widely recognized. Future mobility solutions are therefore expected to consist of Shared and Automated Vehicles (SAV). This means that the passenger experience will take center stage in the design of future road vehicles. Whereas at first sight this may not appear to be different to the experience in other modes of transport, automation and shared mobility introduce different psychological, physical and physiological challenges. These are related to the fact that the occupant is no longer in control, has to put his or her life in the hands of a computer, while at the same time expects such future vehicles to render travel time more efficient or pleasurable and engage in so-called non-driving related tasks. Taking inspiration from work conducted in the field of aircraft passenger comfort experience, we discuss major comfort factors in the context of SAV and highlight both similarities and differences between transport modes. We present a human centered design framework to assist both the research agenda and the development of safe, usable, comfortable, and desirable future mobility solutions.

Keywords: vehicle automation, shared mobility, user requirements, human centered design

1 Introduction

The transport sector is witnessing unprecedented changes, if not revolutions, which are best summarized and memorized by the acronym CASE: Connected, Automated, Shared, and Electric vehicles. The expectation is that the convergence of these developments will transform transport, improving road safety, traffic efficiency, pollution, productivity, and accessibility, while also creating new business models and industries [1]. Each of these developments have also implications for comfort. For instance, electrification allows for a smoother and quieter ride, whereas anxiety may occur when the driver is unsure the battery has sufficient juice to make it to the next charging station. Connectivity allows for internet in-vehicle internet services and for vehicles to communicate with each other (vehicle to vehicle, or V2V) or infrastructure (vehicle to infrastructure, or V2I) to inform you of the most appropriate speed to safely and comfortably merge with the motorway traffic (i.e. lane merge assist), for example. Badly designed user interfaces, on the other hand, may lead to distraction, confusion, frustration, and ultimately disuse [2]. Connectivity is often also considered a prerequisite for full-scale deployment of vehicle automation. In essence, automation refers to the transfer of vehicle control from the driver to the car. Not only has this the potential to avoid the causes of human error (e.g. distraction, inattention, inebriation, fatigue) and suboptimal behavior (e.g. inappropriate time headways and speeds), it also provides the ultimate comfort in that it allows the driver to do something other than driving, whether this involves simply relaxing, catching up on emails, conversing with other passengers, or reading the news.

Perhaps surprisingly, however, comfort is a double edged sword in this context. The increased level of comfort is likely to make the journey more productive or enjoyable and lead individuals to accept longer commuting times, potentially leading to increased urban sprawl and vehicle kilometers. Ultimately, this may negate the potential benefits of automation, or, in fact, lead to even worse outcomes compared to our current situation [3]. The only way we are able to achieve the benefits these technologies may bring is to ensure that the largely non-technological aspect of shared mobility is realized. As a society, we will have to come to accept that private car ownership can no longer remain the norm. Whether it is in the form of ride-hailing, ride-sharing, car-sharing, or any combination thereof, shared mobility is increasingly being considered the essential ingredient for any sustainable future transport solution [3,4,5]. As such, it therefore seems most unfortunate that today nearly every university, research institute, Government, or car manufacturer has a dedicated CAV (Connected and Automated Vehicle) as opposed to SAV (Shared and Automated Vehicle) unit.

In light of the above discussion, the main aim of this paper is to facilitate the research and development, design, and, ultimately, the introduction and acceptance of Shared and Automated Vehicles. In recent years, we have seen several concept SAVs presented at motor shows by various design houses, automotive manufacturers and suppliers. Whereas these present evocative, and sometimes provocative, future visions, they tend to be designed around technologies rather than humans. Unintentionally, these concept cars provide perfect case studies for the human factors researcher and highlight the perhaps unexpected difficulty in making such vehicles work.

There are at least four major challenging factors that affect not only physical, but also psychological and physiological aspects of comfort. These include: 1) the loss of vehicle control, 2) the coexistence of automated and conventional vehicles, 3) the fact that these vehicles are moving, and 4) people's expectations of these technologies. As a consequence, we cannot simply think of such vehicles as living rooms, offices, or entertainment venues on wheels [6]. Furthermore, analogies with other modes of transport, including taxis, trains, and buses, only partially hold true as will be discussed in more detail below. For clarity, however, we first introduce a brief overview of what we mean by vehicle automation and shared mobility.

1.1 Defining Shared and Automated Vehicles (SAV)

Vehicle automation refers to the transfer of the driving task (vehicle control and monitoring of the environment) from driver to car. Currently, the automotive industry is adopting an evolutionary approach. Level 2 or partially-automated driving [7] has already been commercialized. Level 2 does not require the driver to physically operate the vehicle in terms of longitudinal and lateral control, but does require the driver to supervise the system to be able to resume manual control at any time. As such, the drivers is not replaced but assisted. From Level 3 upwards, the driver is no longer required to monitor the environment and is thus able to engage in non-driving tasks under certain conditions. Level 3 (Conditional automation) would still require the driver to regain manual control if required within a certain time buffer, e.g. within 30 s following a warning signal. The necessity to regain control in levels 0-3, and the difficulty humans have monitoring and safely intervening when automation fails [8], has led others, such as Google, to follow a revolutionary approach and jump to Level 4 and 5. Level 4 (High automation) no longer requires the driver to intervene, but the autonomous mode may not be available on all types of roads. Finally, at level 5 (Full automation), the vehicle can perform all driving functions and monitor roadway conditions for an entire trip. The SAE categorization has received the necessary criticism due to its largely technology and feature driven nature. In the current context, the essential dichotomy in vehicle automation is between supervised (Levels 0-2) and unsupervised automation (Levels 3-5). Further, it should be pointed out that automation is not restricted to passenger (M1) vehicles but also so-called first and last mile mobility vehicles, or autonomous pods, operating at Level 4 but at relatively low speeds and restricted areas are expected to provide valuable contributions to future transport systems (e.g. Alessandrini et al. 2014).

As pointed out by Fulton et al. [3], the term shared mobility is often incorrectly used. Ride sharing (or trip sharing or shared mobility) refers to rides or trips that are actually shared between different individuals or different parties and paid separately. Ride hailing (or ride booking) refers to any app-based system to secure a ride from a taxi or other "on-demand" ride service provider such as GrabTaxi, Uber, Lyft, Ola, or Easy Taxi. These rides may or may not be shared. Strictly speaking, on-demand ride-hailing services are not ride-sharing services unless they exclusively offer shared rides as may be the case with the first and last mile mobility solutions discussed above. For the current discussion, however, we here also define "robot taxis" as shared mobility in that the vehicle is shared across individuals.

1.3 Major factors challenging the comfort experience in SAV

The overall comfort experience is here modelled as a point on a fragmented continuum between comfort and discomfort whereby comfort can be defined as "a pleasant state of well-being, ease, and physical, physiological and psychological harmony between a person and the environment", while discomfort refers to "a state where one experiences hardship of some sort which could be physical, physiological or psychological" [9]. Whilst it is easy to argue that comfort and discomfort can occur simultaneously and are not polar opposites, the concept is kept uncomplicated here.

As mentioned earlier, there are at least four major factors that challenge the comfort experience of occupants in SAVs. The implications of the different factors will be discussed in more detail in the next section in which it will become apparent that these factors are not independent but interrelated instead.

- **Loss of control**: The transfer of control lies at the heart of any automation. In the context of SAV, this refers to the (partial) transfer of vehicle control to the car or system. Automation renders occupants system monitors and, ultimately, passive passengers.
- **Coexistence**: The introduction of automation will not happen overnight. As a consequence, automated vehicles will be sharing the space with conventional vehicles but also vulnerable road users (pedestrians, cyclists, horses). Segregation of SAV may be envisaged but will limit the operational envelope of the technology and is unlikely to be accepted by society.
- **Moving environment**: The vehicle dynamics will be heavily dependent on the actual SAV implementation, e.g. low speed urban traffic versus high speed motorway traffic. Furthermore, vehicle dynamics can be expected to differ considerably from most public road transport (bus, train, metro) which largely involves relatively long distances at constant speeds. This has inevitable knock-ons to the biomechanical response of the vehicle occupant and could influence comfortable postures and tasks.
- **User expectations**: Vehicle automation is marketed and presented as enabling users to engage in various non-driving related tasks ranging such as sleeping, reading, or conversing. The technology promise and expectations may not necessarily match, in particular during the critical introductory phase.

The fundamental underlying aspect related to the above factors is that both vehicle automation and shared mobility is entirely focused on the passenger experience. The traditional driver-focused design approach is no longer valid and requires an entire recalibration of products and processes, whereby the relative importance of vehicle attributes is also likely to shift [10]. Despite the fact we have had passengers for as long as we had cars, i.e. for over a century, the passenger experience is not prioritized for road vehicles. The passengers have been largely neglected by the automotive industry as illustrated by the vast differences in trim levels and budgets between front and rear compartments, the absence of any car reviews *not* focusing on the driver, and the inability for anyone above the 80^{th} percentile in stature to comfortably travel in the rear of virtually any vehicle. However, given the extremely low occupancy rates of cars (e.g. rates barely exceed 1 during commuting), the automotive industry is not to blame and only higher car occupancy rates will be able to shift this focus.

In the meantime, SAV may benefit from looking at other industries that traditionally have focused on the passenger experience. When considering expectations and the conditions under which SAV are considered to operate, it becomes apparent that the aviation industry may provide a suitable inspiration. Here, the passenger experience has long been recognized as a commercial differentiator. For example, 35% of passengers on intercontinental flights base their choice of airline on comfort, placing it after flight schedules [11]. Recently, Ahmadpour et al. [12] conducted a large scale survey amongst long-haul flight passengers to identify key factors associated with the passenger comfort experience. A factor analysis of 60 comfort descriptors revealed eight main factors. From most to least important these included: peace of mind, physical wellbeing, proxemics, satisfaction, pleasure, social, aesthetics, and association. They provide a useful starting point to think about the different factors that may also be of relevance in the context of the passenger comfort experience in SAV while acknowledging fundamental differences between the two transport modes.

First, with the exception of occasional periods of air turbulence, the motion profile of an aircraft largely consists of constant velocity motion. Due to the fact that our organs of balance only sense changes in velocity [13], we sense no motion and experience the in-flight environment as stationary. In contrast, the motion profile of road transport involves extensive lateral and longitudinal accelerations (e.g. start-stop traffic, cornering, and lane changes), as well as high frequency vibration [14]. Secondly, compared to air travel, the road environment is an extremely high risk environment where miscalculations, measured in centimeters and milliseconds, can be fatal. Air travel, on the other hand, enjoys a high level of slack as also reflected in being the safest mode of transport. Third, lower levels of road vehicle automation require shared vehicle control between the driver and the car. Semi-automation will expect the driver to regain vehicle control when the vehicle has reached the limits of its operational envelope (e.g. no road markings available on road). Bringing the driver back in the loop is a classic human factors problem and also one of the main concerns in road vehicle automation [15]. Whereas this automation issue of course also exists, and in fact originated from the field of aviation, a fourth difference is that we can rely on professional trained pilots to deal with this problem. New driver training requirements for an automated future are being discussed, however, it may be unrealistic to expect the same level of skills, capabilities, and behaviors from the general driving population.

Reflecting on these differences, it becomes apparent that the user and subsequent design requirements for the passenger experience in road vehicles may differ considerably. In the below, we provide an initial framework with the aim of guiding the design of future vehicles while identifying gaps in knowledge and areas of future research. Please note that at this stage, the framework is not intended to be exhaustive nor, for obvious reasons, validated.

2 Conceptual framework for the comfort experience in SAV

Figure 1 shows eight preliminary factors that are expected to be of particular relevance for the passenger comfort experience in SAV. For reasons of brevity, we will only provide an initial overview of each of the factors and refer to some example research studies for illustration purposes.

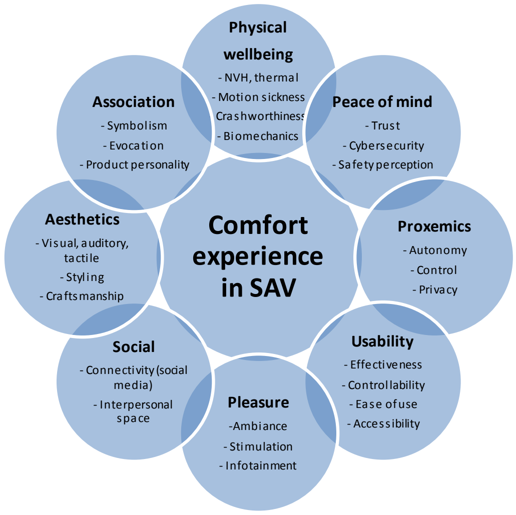

Fig. 1. Conceptual framework for the design of the passenger experience in Shared and Automated Vehicles (SAV).

Physical wellbeing
Arguably, together with peace of mind, physical wellbeing is the most critical aspect to enable the perception of comfort. Referring back to the major factors challenging the comfort experience in SAV, coexistence of automated and conventional vehicles means that occupant safety and related vehicle crashworthiness will remain largely unchanged at least until we have achieved sufficiently high penetration rates of automated vehicles, or segregate them from conventional traffic. Whereas the automated vehicle may be smart and safe, there is no guarantee that other vehicles may collide with it. This fact alone has considerable ramifications in terms of the design of user interactions and render visions of rotating seating arrangements or the use of nomadic devices (i.e. tablets, laptops) problematic unless passive safety systems (e.g. airbags) are being developed accordingly. Similarly, the need to retain current interior layouts and associated confined spaces makes it extremely challenging to develop HMI concepts that allow us to comfortably (i.e. postural comfort) and productively (i.e. efficient input devices) engage in so-called Non Driving Related Tasks (NDRT). We can also expect that users will become increasingly perceptive of the vehicle performance in terms of noise, vibration, and harshness, as well as thermal comfort, simply due to the fact that he or she is no longer engaged in an meaningful task, i.e. driving [16,17]. With energy management being a major concern in the context of electrification and HVAC use for example, this raises the question whether we ought to consider the concept of acceptable versus optimal comfort perception [18]. This discussion will also become relevant when considering the fact that comfortable vehicles tend to be large and heavy, contradicting the trend towards lightweight and efficient vehicles. Finally, the impact of a moving environment and no longer being in control of a vehicle affects comfort in a number of ways. First, biomechanically, we can expect the passive passenger not holding on to a steering wheel to be shaken around significantly more which opens up the opportunities for novel seating design solutions. Secondly, we can expect significantly higher levels of carsickness in SAV compared to conventional vehicles due to the fact that the passenger is less able to predict the oncoming motion profile while also sensing conflicting motion cues when engaged in NDRT such as reading in the vehicle [6,19,20]. On-road studies suggest that under such conditions carsickness may be experienced by as much as 50%-75% of the population [21,22].

Peace of mind
On par with physical wellbeing, peace of mind will be essential for the successful introduction and uptake of SAV. The major challenge for automated and shared vehicles is to instill a sufficient and appropriate, or calibrated, level of trust [24]. Trust develops over time, but can be facilitated by providing the right type of information. Research thus far seems to suggest a holy trinity of mode awareness (i.e. who is in control of the vehicle), situation awareness (i.e. what does the vehicle see), and behavioural awareness (i.e. what is the vehicle going to do next) [23]. Future research will be required to understand how best to represent this infor-

mation although initial studies already point towards the intricate and interrelated nature of comfort as illustrated by the role of HMI aesthetics in instilling system trust [25]. Interestingly, trust in fellow passengers may appear to be less challenging than one would expect. A study by BlaBla car ride-sharing company revealed that, rather surprisingly, fellow users enjoyed higher levels of trust than work colleagues or neighbors [26]. Another challenge pertains to the concerns around cybersecurity [27]. Recent reports about hacked vehicles have raised awareness around the vulnerability of current automotive systems and will have to be addressed to ensure customer confidence.

Proxemics and Social

Proxemics, as interpreted in Ahmadpour et al's [12] study, refers to the experience of privacy and control over one's environment. This factor appears to show considerable overlap with the social aspect of the comfort experience and, for brevity, is discussed jointly. Whether it is for business or for pleasure, using our time more constructively as enabled via SAV can be regarded as a game-changing proposition. How we want to use this time will dependent on several factors but in the extreme we can make a distinction between a "stagecoach" or "shared space" model which facilitates social interactions, for example by positioning seats towards each other, versus a "cocoon" or "individual space" model which emphasizes the independence and isolation of the individual. We can observe a similar dichotomy in the digital realm where we can see user interaction concepts facilitating individual connectedness (i.e. social media) to the outside world versus a shared digital experience within the vehicle. Here we can imagine different types of vehicles depending on an individual or shared experience, but of particular interest may be the ability to swap between these two experiences.

Usability

We here refer to usability as the effectiveness, efficiency and satisfaction with which users achieve their goals. As mentioned, the ability to engage in leisurely or economically productive non-driving related tasks, is at the heart of the proposition put forward by vehicle automation, and by extension shared mobility. However, as already discussed in the above section on physical wellbeing, the ability to do so in a confined and moving environment is far from trivial [20]. The use of existing interaction paradigms, e.g. mouse and keyboard, in an automotive environment is cumbersome and particularly difficult to implement in semi-automated vehicles requiring the driver to regain control within set time limits. User expectations play an important role here too. The ability to free up our time to engage in more useful or enjoyable activities is pertinent to vehicle automation. Whereas we may elect not to use public transport or accept that we won't be able to use our laptop sitting in the passenger seat as it makes us feel queasy, the proposition of vehicle automation differs. The benefits of automation may not be perceived significant unless we can actually engage in other activities. In fact, the inability to do so, and in the worst case, having to constantly monitor the system and environment, may well be perceived as less comfortable and acceptable than manual driving [21].

Pleasure

SAV will provide unprecedented opportunities to enhance the experience within the vehicle. This can be trip related (e.g. geo-specific information), an entirely decoupled immersive experience, or a wellbeing spa on wheels. We have seen several concept vehicles indulging in variations of such future scenarios. However, to date, these concepts may not have sufficiently appreciated some of the other challenges associated with SAV in particular with reference to the factors of physical wellbeing and peace of mind. The future challenge lies in enabling such new experiences while ensuring that more basic requirements are respected. Conversely, we also need to take into account the effect of time and experience and we may need to balance system trust and the ability to comfortably engage in non-driving tasks in favor of the latter, for example [28].

Aesthetics

Aesthetics is sometimes mistakenly referred to as "styling". As with any product, the appearance is of utmost importance, referring to not just the visual but also the haptic, tactile, auditory, and olfactory sensations. Material and trim options form a particular challenge given the hygiene, durability and maintenance requirements in SAVs. To date, the aesthetics of the experience have largely been neglected and, understandably, the focus has been on demonstrating the technological capabilities and feasibilities of SAVs. However, when only considering the visual appearance of SAVs, we can expect it to play a vital role in public perception and acceptance since it signals a wide range of attributes [29]. As an example of the impact the visual appearance can have in the context of comfort, changes in the visual appearance of otherwise identical seats dramatically affects the perception of seating comfort [30].

Association

Following on from the above, the associations related to a product, including its appearance, can have considerable implications. Vehicles are considered "avatars", or extensions of oneself [31], and psycho-social aspects have to be taken into account when introducing a new type of transport. This is illustrated by the social stigma attached to bus and coach travel in the United States. Efforts to provide more upmarket interior designs for long distance coach services have been successful in making customers feel comfortable in using these services. Similarly, in particular last mile mobility solutions providers and operators need to be mindful of the effects association and exterior design can have on future use [32].

3 Conclusion

Shared and automated vehicles (SAV) have the potential to provide a positive contribution to today's transportation challenges. As yet, most of the development has focused on the technological feasibility of such vehicles without sufficiently taking into account the human factor, particularly in the context of the anticipated vehicle-user interactions. Future vehicles will be entirely focused on the passenger experience and understanding the passenger requirements in a future of shared and automated vehicles is expected to become an important line of research. We here presented an initial framework around major factors influencing the passenger experience to guide the vehicle design process and highlight gaps of knowledge and areas for future research.

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