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Objective metrics of comfort: Developing a driving style for highly automated vehicles

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ABSTRACT

This paper addresses the issue of enabling a comfortable highly automated driving style. Two studies have been conducted to identify metrics which can be used to parametrize a high-quality automated driving style for automobiles with regard to safety, functionality and comfort. The studies were set either in an urban and rural or a highway environment. Participants ($N = 12$ per study) manually drove a round course assuming either an everyday, a comfortable, or a dynamic driving style in randomized order. The obtained results emphasize the importance of maneuver-based analysis. Namely, a variety of maneuver-specific metrics, such as acceleration, jerk, quickness and headway distance in seconds, were identified, which are prerequisites to differentiate between the three driving styles. These metrics seem to be the essential components for the development of comfortable highly automated driving.

1. Introduction

Throughout the last years a major topic in automotive industry has been automated driving. Together with the central question of when the technology will be ready to be widely introduced, research has focused on topics such as attentiveness issues, situation awareness, engagement in secondary tasks, distraction, and driver monitoring. We believe all of these topics to be important but want to address a more fundamental challenge: How does a highly automated vehicle need to drive in order to meet a – now passive – driver's expectations?

When being a passenger in a human-driven vehicle our feeling of comfort is primarily based on the driver's driving style (Ellinghaus & Schlag, 2001). We believe that the same applies when being a passenger in an automated vehicle. Thus, we find it crucial to identify the essential components of an automated driving style which give passengers a maximum amount of comfort and ease. Throughout literature there is no uniform definition of comfort. Thus, in this paper comfort is understood as a state which is achieved by the removal or absence of uneasiness and distress.

Elander, West, and French (1993) define the concept of driving style as a habitual way of driving, which includes a person's preference of velocity, their individual conditions for overtaking, preferred headway distance and how strictly they abide traffic laws. Other studies also explicitly mention the importance of acceleration behavior, which is a natural result of different preferences for velocity changes, in differentiating driving styles (see e.g. Müller, Hajek, Radic-Weissenfeld, & Bengler, 2013; Reiser, Zellbeck, Härtle, & Klaiß, 2008). Many studies have divided the concept of driving style into three

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styles: comfortable, dynamic, and everyday driving (Langari & Won, 2005; Murphey, Milton, & Kiliaris, 2009; Vlieger, Keukeleere, & Kretzschmar, 2000). This implies that the perceived comfort should be maximal for comfortable driving and minimal in dynamic driving. Lange, Maas, Albert, Siedersberger, and Bengler (2014) have found that automated driving does not have to be less dynamic than manual driving to be perceived as comfortable. Thus, results based on manual data should be a good indicator of which automated driving style may be perceived as comfortable.

As automated driving needs to offer a high level of comfort, the aim of our research is to identify maneuver specific objective metrics which are able to classify driving as comfortable, dynamic, or everyday driving and can be used to parametrize automated driving in an optimal way.

There have been multiple studies in the past addressing the issue measuring and assessing manual driving styles. Many studies are based on questionnaire data (Møller & Haustein, 2013; Reason, Manstead, Stradling, Baxter, & Campbell, 1990; Taubman-Ben-Ari, Mikulincer, & Gillath, 2004). Others have used objective data but have exclusively focused on speed and/or acceleration (e.g. Doshi & Trivedi, 2010; Vlieger et al., 2000). Moreover, further studies have used multiple metrics but relied on algorithms which summarized data of road types without regard for the individual maneuvers driven (Ericsson, 2000). In our research, however, automated driving makes it necessary to obtain objective data, which can be used to parameterize an automated system. Additionally, it is essential to split a trip into different maneuvers in order to achieve a feeling of comfort not only on the whole but for every second along the way.

This paper describes two studies. The first study was conducted on rural, suburban and urban roads with a maximum speed of 100 km/h (62 mph). The second study was conducted on a highway with a maximum speed of 120 km/h (75 mph).

For maneuver-specific analysis we chose maneuvers, which are common in both the urban and rural as well as the highway setting. For this cause we counted the frequency of maneuvers stated in literature (see i.e. Manstetten, 2014; Toledo, Musicant, & Lotan, 2008; Wu, Yeh, & Chen, 2014) in 1008 km of real roads. This resulted in four main maneuvers:

1. *Decelerating to a moving target* (approx. 16% of maneuvers)

   The ego vehicle decelerates from a steady velocity upon closing in on another vehicle, which is driving at a non-varying lower speed.

2. *Accelerating from non-zero speed* (approx. 18% of all maneuvers)

   The ego vehicle accelerates from a non-zero speed to a goal speed without a leading vehicle.

3. *Lane change* (approx. 20% of all maneuvers)

   The ego vehicle changes lanes. This can be to overtake another vehicle or for navigational purposes.

4. *Following at a non-varying speed* (approx. 27% of all maneuvers)

   The ego vehicle follows another vehicle. Both vehicles maintain a steady velocity.

For each maneuver a variety of data where obtained. As the vestibular system plays a key role in not only the development of nausea or motion sickness (Reason, 1978) but also in the perception of driving in general (Lange et al., 2014; Müller et al., 2013), we have focused on metrics which cannot only be manipulated in an automated system but can also be perceived by the vestibular system. Humans' vestibular system is not able to perceive speed itself, but perceives changes in speed – acceleration. Strong acceleration on its own can lead to an impaired feeling of comfort or even nausea. However, humans are even more sensitive to rapid changes in acceleration – jerks – than to acceleration itself (Gianna, Heimbrand, & Gresty, 1996; Probst, Krafczyk, Büchele, & Brandt, 1982). In the reported studies we have recorded both acceleration and jerk. *Mean acceleration* is able to analyze the maneuver as a whole or in larger segments. Analyzing the first derivative of acceleration – *jerk* – allows specific points in an acceleration to be easily identified in the maneuver where acceleration changes rapidly. We propose multiple peaks of jerk occur throughout the longitudinal maneuvers (see Fig. 1). Thus we have decided to not only look at the maximum jerk within each maneuver, but to analyze two jerks in the maneuver *acceleration from non-zero speed* and two or four jerks respectively in the maneuver *deceleration to a moving target*. The first jerk within the acceleration maneuver is the *maximum absolute jerk recorded upon pressing the gas pedal*, while the second jerk represents the *maximum absolute jerk upon releasing the gas pedal. Deceleration to moving target* can be split into two or four jerk-relevant subsections. This depends on whether brakes are applied or not. Here, the first jerk is the *maximum absolute jerk upon release of the gas pedal*, the second and third jerk describe the *maximum absolute jerks upon pressing* and *upon releasing the brakes*. These jerks can only be observed when brakes are used. Finally, the fourth jerk describes the *jerk upon pressing the gas pedal* again.

In addition to the widely used metrics of acceleration and jerk the metric *quickness* will be analyzed throughout the studies. *Quickness* describes the swiftness with which a maneuver takes place, thus being able to describe characteristics of the maneuver as a whole. The metric is used as a performance measure in the assessment of flying qualities of aircrafts and especially helicopters (Padfield, 2007). In our studies we have adapted the measure to automobile conditions. *Longitudinal quickness* q_{long} is defined as $q_{long} = \bar{a}/\Delta v$ by the m*ean longitudinal acceleration* $\bar{a}$ and the *change in longitudinal velocity*