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Determining maximum velocity for automated driving functions

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Summary

Vehicle automation will be introduced stepwise to the consumer market. On an initial level, it is likely that these functions are going to operate only within a limited velocity range or only in a limited number of use cases (e.g., in traffic jams). Consequently, the frequency of state transitions to lower levels of vehicle automation as well as the time the driver can actually use the automated driving function would, among other factors, depend on the threshold of the maximum speed limit. It may be assumed that the perceived usefulness – and thus the acceptance – of a feature will be heavily influenced by the frequency of transitions and the availability of the assistance function. Also, the occurrence of state transitions from automated to manual driving is relevant for safety considerations, as each transition can be considered a potential source of human error. This paper describes a field study that aims at assessing the impact of different velocity thresholds of automated vehicle functions on the frequency of state transitions and the function's availability during a field study in a metropolitan area in Germany. The drives (N = 96 drives, approx. 30 min each) took place in rush-hour traffic. Based on the results, it may be recommended to either set the velocity threshold to 60 km/h, covering jammed traffic, or above 110 km/h, covering the full speed range, in order to increase the availability of the automated driving function and in order to avoid unnecessary state transitions.

1 Introduction

Automated driving functions are already commercially available. For example, partially automated driving functions in traffic jams keep a safe following distance to other vehicles and also hold the vehicle in the lane (e.g., Petermann-Stock, Hackenberg, Muhr & Mergl, 2013; Schaller, Schiehlen & Gradenegger, 2008). Because the driver still has to monitor the driving situation, these functions are called "Partial Automation" (Gasser et al., 2012). Currently, even higher levels of vehicle automation are under development (de Winter, Happee, Martens & Stanton, 2014). For example, the EU-founded project AdatIVe aims at developing so-called "Highly Automated Driving" functions that even allow the drivers to disengage from the driving task until a take-over request is issued (Wiedemann, Schömig, Mai, Naujoks & Neukum, 2015). It is currently expected that these driving functions may be available by the end of this decade (Spölder & Abel, 2014). Regarding marked introduction, it is likely that these functions will firstly be operating in a limited number of use cases. A probable use case may thus be assistance in traffic jams on motorways (Lücke, Fochler, Schaller & Regensburger, 2015).

Because of functional safety considerations, the assistants' maximum operating speed may initially be limited to low ranges of velocity. However, from the drivers' point of view, the limitation of the operating speed can be viewed as a key factor for both *safety* and *acceptance* of the automated driving function:

- Concerns have been expressed that being "*out of the loop*" during automated driving may lead to a decrease in the driver's situation awareness and the ability to safely take over manual vehicle control (in case of take-over situations, see de Winter et al., 2014). Several studies suggest that take-over situations may be demanding and, if the driver does not take back vehicle control timely enough, potentially dangerous (e.g., Naujoks, Mai & Neukum, 2014; Merat et al., 2014; Gold, Damböck, Lorenz & Bengler, 2013; Damböck, Weissgerber, Kienle & Bengler, 2013). Thus, it can be expected that designing automated vehicle functions that minimize the frequency of transitions between driving modes (i.e., manual driving ↔ automated driving) would increase driving safety and comfort. It is expected that the maximum operating speed will be directly related to two types of human-automation interactions: During automated driving, every time the speed limit is reached, the driver will have to interact with the system (see Dogan, Deborne, Delhomme, Kemeny & Jonville, 2014), either by 1.) *activating* it (when speed drops below the operating speed) or 2.) by *taking over manual driving* (when speed increases to the maximum operating speed). In the latter case, a take-over request would possibly be issued to the driver. Take-over requests are communicated to the driver by the vehicle's Human-Machine Interface (HMI). They are viewed as a key factor for safe and efficient human-machine interaction with automated vehicles as well as user experience when using automated driving functions (e.g., Naujoks et al., 2014; Wiedemann et al., 2015; Lorenz, Kerschbaum & Schuhmann, 2014; Beller, Heesen & Vollrath, 2013). However, minimizing the frequency of state transitions (i.e., manual driving ↔ automated driving) will prevent possibly dangerous situations and annoying drivers by issuing too many take-over requests at the same time.
- On the other hand, the maximum operating speed also directly determines how often the automated driving function will be available to the driver. For example, if the maximum operating speed would be set to 30 km/h, the availability during a drive would possibly be lower compared to an operating speed of 50 km/h. However, studies investigating the influence of the maximum operating speed on the frequency of human-machine interactions and availability of the respective automated driving functions are currently not disposable.

It can be expected that the availability of the function, as well as the frequency of interactions (activation, take-over request) may determine the subjective usefulness, and in turn, the acceptance of the driving function (Davis, 1989). This study takes a practical approach in assessing the impact of different speed thresholds on the availability of a hypothetical automated driving function. We conducted field trials in congested rush hour traffic in a metropolitan area in Germany. Thus, the availability and interaction frequency resulting from different hypothetical speed thresholds can be analyzed using these on-road data. The field trials were conducted on different days with N = 32 participants. This approach – in contrast to technical field-testing by trained personnel – additionally allows accounting for different driving styles. Suggestions for the optimal setting of the maximum operating speed for automated driving functions are derived from the analysis of the speed profiles.

2 Method

2.1 Test site and procedure

The purpose of the study was to investigate the velocity distribution and time-series of the velocities chosen by different drivers during rush hour traffic in a metropolitan area. A suitable road structure was found in the metropolitan area of Stuttgart, which ranks number six among the European cities in the TomTom Congestion Index. The test drives took place on a fixed section of the highways A8 and A81 in the metropolitan area of Stuttgart. The test route consisted of a three-lane highway. The test route had no speed limit for the most part. All test drives took place in morning or evening rush hour traffic in January 2014. The drivers that participated in the field trial executed three consecutive drives of 30 minutes, respectively, allowing the drivers to rest between the drives. The drives took place between the exits Leinfelden-Echterdingen (A81) and Rutesheim (A8). The field trial lasted approx. four weeks in January 2014.

2.2 Sample

The participants were recruited from a pool of over 150 potential candidates that were contacted through advertisements in newspapers prior to the study. The sample consisted of 8 female and 24 male drivers. At the time of the test, the median age of the drivers was 47.19 years (*SD* = 16.08, *MIN* = 20, *MAX* = 70).

2.3 Dependent measures

A total of N = 96 drives were collected, each lasting approx. 30 minutes. Thus, the data set represents roughly 48 hours of driving in rush-hour traffic. Time-series of the velocity were collected and analyzed per drive (measurement rate 1 Hz). Our approach makes it possible to account for the influence of different driving styles (within the participant sample) and driving days when analyzing the data. Two parameters are analyzed in this study:

- *Availability* of the hypothetical automated driving function: Relative frequency of time, the automated driving function would be available, given the respective operating speed

- *Frequency of transitions*: Frequency of mode transitions given the respective operating speed, i.e., activation when speed drops below the maximum operating speed and take-over request when speed increases above the threshold;

3 Results

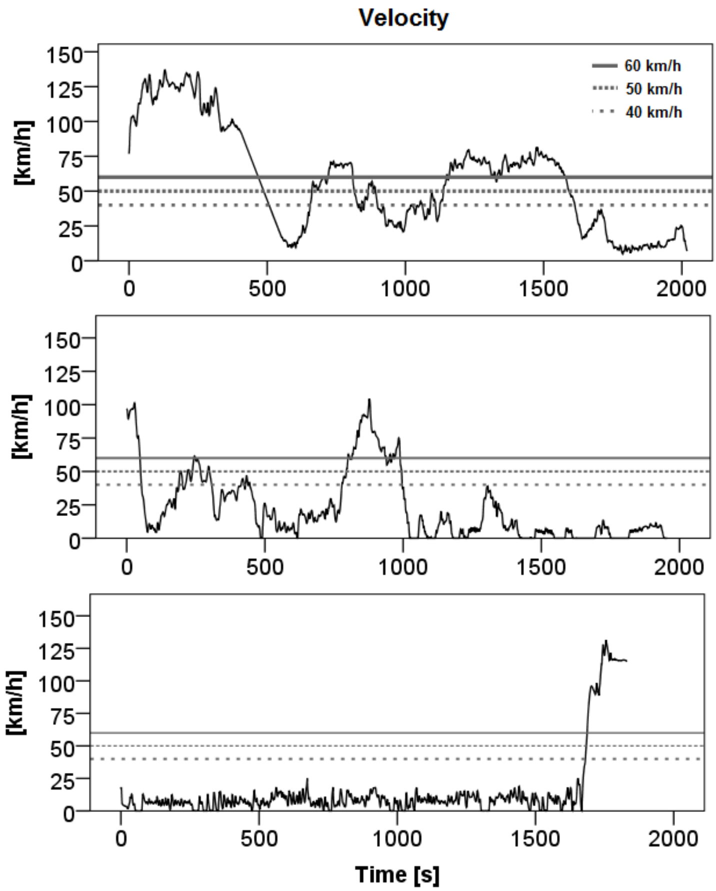

Figure 1: Sample plots of different time-series of driving velocity (each plot represents one drive). The horizontal lines in the graph represent different hypothetical velocity limits.

Figure 1 shows samples of the time-series of different velocities driven by participants during test drives on different days. The horizontal lines represent different hypothetical velocity thresholds of an automated driving system. As can be seen from the figure, both the *availability* and the *frequency of transitions* depend both on the respective speed profile and the maximum speed threshold:

- The bottom of the figure shows the velocity during a test drive in completely jammed traffic. The operating limit of the assistance function is only reached when the traffic jam dissolves, independently of the maximum speed threshold.
- The samples in the middle and on top of the figure show test drives in which the velocity fluctuated between higher driving speed and standstill (middle) or near standstill (top). Here, it becomes clear that the threshold value would definitely impact both the availability of the driving function as well as the number of transitions (non-available → available when the speed drops below the maximum operating speed and active → take-over when the speed increases above the maximum operating speed).

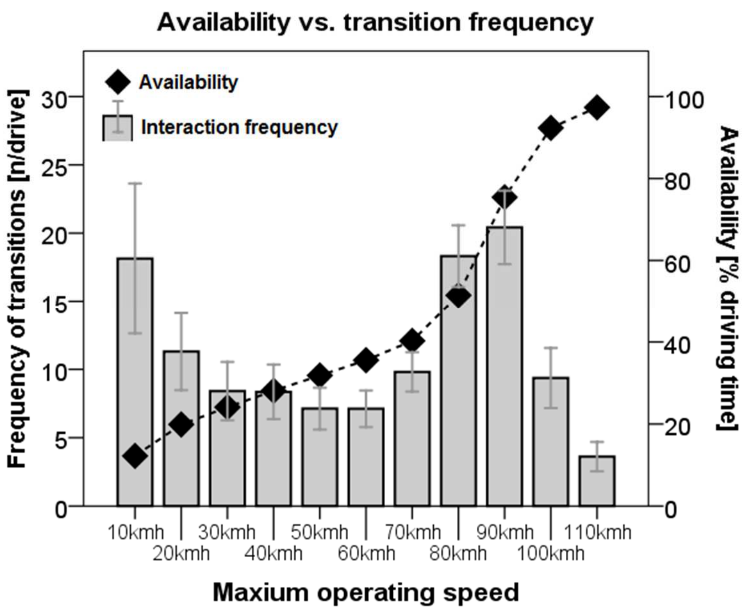

Figure 2: Availability of the automated driving function vs. frequency of transitions. Activation and take-over request are summarized as "transitions" in the analysis.

In Figure 2, the result of the analysis of the whole data set is shown. Grey bars represent the average number of transitions between driving modes (which would require an action by the driver) while the line represents the relative frequency of time the automated driving function would averagely be available to the drivers. Several conclusions can be drawn from the figure:

- The *availability* of the function increases steadily with increasing maximum operating speed. However, this increase is not linear. Allowing the automated driving function to operate at speeds < 80 km/h would lead to an availability of only about 40% of the driving time. In contrast, maximum operating speeds of 80-100 km/h would lead to a sharp increase in the system's availability. Above these maximum speed thresholds, speed ranges of more than 110 km/h would not add to the availability considerably.

- The distribution of the *frequency of transitions* (= transitions between driving modes) is bimodal. The first peak of the distribution is due to low-speed driving. Increasing the operating speed from the low-speed range of >20km/h up to 60km/h would lower the frequency of transitions considerably. The second peak is found in the operating speeds 80 km/h and 90 km/h. In this speed range, transitions from congested to free flow traffic (and back) take place, increasing the frequency of state transitions of the automated system.

4 Conclusions

Based on this analysis, design recommendations for the maximum operating speed are derived. The data collected in the field trail show a clear relationship between the maximum speed threshold and the frequency of state transitions that would be communicated to the driver via the HMI of the hypothetical driver assistance. Lowering the frequency of take-over requests by the automated driving function's settings can be viewed as a key factor for the perceived usefulness and acceptance of the respective driver assistance. This assumption is based on human factors research which has shown repeatedly that take-over situations are demanding driving situations that may be annoying or – in the worst case – even lead to dangerous driving situations (e.g., Naujoks et al., 2014; Merat et al., 2014; Gold et al., 2013; Damböck et al., 2013). On the other hand, the maximum speed threshold was directly related to the availability of the hypothetical driver assistance during the drive. Availability may be viewed as being directly connected to the perceived usefulness of the automated driving functions. Considering the impact of the maximum operating speed on both availability and transition frequency together, it can be concluded that:

- The automated driving system should either cover a speed range between 0 km/h and 60 km/h, or that it should be available in the full speed range.
- Specifically, making the automated driving system available in a speed range above 110 km/h would have maximized the system's availability and reduced the frequency of state transitions in the current field trial.
- On the other hand, Limiting the functionality to a maximum velocity of 80 km/h - 90 km/h would have lead to an unnecessary increase in the transition frequency and would have lowered the system's availability considerably.

The proposed velocity ranges indicate that – with regard to the maximum operating speed – automated driving functions should either be provided in congested traffic (up to a maximum speed of 60km/h) or that they should be able to cover driving speeds above 110 km/h. It should be noted, however, that our conclusions may be limited to the use case at hand. Specifically, our field study covered the use case of rush-hour traffic in a metropolitan area on a multi-lane highway. Congested traffic is encountered frequently on this highway. It is possible that the results do not generalize to other areas that do not exhibit the same traffic flow properties, especially with regard to the distribution of driving speeds. Published data on this topic are currently not available and it is thus not possible to estimate the generalizability of our results.

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