Longitudinal Acceleration during Lane Changes - A Human-Centered Investigation for Automated Driving

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Abstract:

Lane changes represent central driving maneuvers on highways and are frequently linked to acceleration maneuvers. For automated driving, previous studies have addressed the issue of appropriate longitudinal accelerations for vehicle occupants. However, these investigations only considered pure longitudinal acceleration maneuvers and have neglected potential influence of lane changes on driving experience. For this reason, this paper presents an evaluation of longitudinal accelerations during non-automated and automated lane changes and compares the results with previous studies. Based on this, the usefulness of further human-centered research on longitudinal accelerations during automated lane changes is discussed and recommendations for a future study are proposed.

Keywords: Automated Driving, Human Factors, Lane Changes, Vehicle Dynamics

1 Introduction

Appropriately designed automated driving styles contribute to increase driving comfort [1] and the general acceptance of automated driving [2]. Besides the tactical decision-making process and question of when which driving maneuver is performed automatically, the operational performance of these maneuvers plays an important role. In particular, longitudinal dynamic parameters, such as longitudinal acceleration, have a strong influence on driving comfort during automated driving [3], which is why a human-centered parameterization is essential in this case. According to a summary of studies on non-automated and automated driving [4], longitudinal accelerations up to $0.9\,\mathrm{m/s^2}$ are considered *cautious*, up to $1.47\,\mathrm{m/s^2}$ are considered *normal*, and up to $3.07\,\mathrm{m/s^2}$ are considered *dynamic*. Further studies on automated driving indicate that longitudinal acceleration profiles should be designed symmetrically [5] and that a longitudinal acceleration of $1.5\,\mathrm{m/s^2}$ should not be exceeded in low-speed zones [6]. In comparison, a relevant standard [7] defines a maximum longitudinal acceleration of $2.0\,\mathrm{m/s^2}$ for adaptive cruise control (ACC) systems and thus, according to the Society of Automotive Engineers (SAE) [8], for the first level of automated driving.

In the aforementioned literature and in consideration of further studies, acceleration maneuvers are mostly investigated independent of lane changes. However, especially

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on highways, lane changes represent main driving maneuvers, which are characterized by interaction with other vehicles [9], a relatively high safety risk [10], a combination of longitudinal and lateral dynamics [11], and resulting quiet complex driving situations [11, 12]. For these reasons, acceleration maneuvers during lane changes are not necessarily comparable to ordinary acceleration maneuvers without lane changes. Therefore, the research question of how longitudinal acceleration during automated lane changes should be designed cannot be answered in detail at the current time. However, it is known that an acceleration maneuver starting shortly before the actual lane change can contribute to the predictability of automated passing maneuvers and the automation system's behavior [13].

In this paper, we investigate on the basis of recorded non-automated and automated lane changes the longitudinal acceleration during passing maneuvers on German highways. Based on this, appropriate maximum longitudinal accelerations during automated lane changes are estimated and recommendations for future human-centered studies are derived.

2 Methodology

This paper focuses on non-automated and automated so-called *tactical lane changes* to the left, which serve to increase speed and to initiate passing maneuvers [14]. Accordingly, the following investigations only take into account lane changes with a lower speed at the beginning of the driving maneuver than the maximum permitted speed in the respective highway section and, if available, than the intended target speed of the automation system. For the estimation of a comfortable longitudinal dynamic and, more specifically, an appropriate maximum longitudinal acceleration during automated lane changes, a three-step methodology was defined:

1. Automated lane changes that were performed under real-world conditions in our last study are evaluated and respective assessments of participants on the longitudinal dynamic are summarized. Since the overarching objective of this study was to identify appropriate moments for automated lane changes [15, 16], the number of assessments of the longitudinal dynamic is severely limited, despite more than 750 automatically performed lane changes to the left.

2. Due to the limited number of available assessments of the longitudinal dynamic during automated lane changes, we also investigate non-automated lane changes using the highD dataset [17]. Similar to the previous evaluation of automated lane changes, the focus lies in this second step on the maximum longitudinal acceleration during passing maneuvers and, moreover, on the potential influence of the traffic scenario.

3. Finally and in consideration of relevant literature, the conducted evaluations of non-automated and automated lane changes are discussed and recommendations for further human-centered research on longitudinal dynamics during automated lane changes are given.

3 Evaluation of Automated Lane Changes

This data evaluation is based on our on-road vehicle study ($N = 60$) focusing appropriate moments for conditionally automated lane changes on highways, which was briefly described in a short paper [15]. Since the main results of this study about appropriate moments for automated lane changes [16] are not relevant for the research issue stated in Section 1, the following explanations concentrate on the test vehicle's behavior planning and the resulting longitudinal dynamic.

The maximum longitudinal acceleration profile was defined on the basis of previous research [13] and is depicted in a simplified form in Fig. 1. Each automated acceleration maneuver was determined individually depending on, among other things, this profile and the difference between the initial speed at the beginning of the lane change and the target speed of the automation system. The target speed of the automation system corresponded to 120 km/h or, if available, to the speed of a slower preceding vehicle. This approach for determining the longitudinal acceleration by means of the speed difference is included in several traffic models [18] and did not distinguish between acceleration maneuvers during lane changes and single-lane acceleration maneuvers in this study.

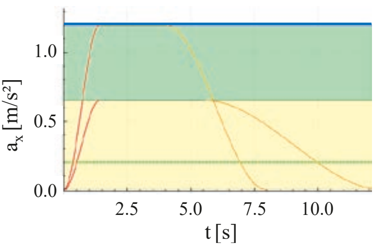

Figure 1: The maximum longitudinal acceleration profile was characterized in our last study by the parameters $a_{x,max} = 1.2\,\mathrm{m/s^2}$ (blue line) and $j_{x,max} = 1.3\,\mathrm{m/s^3}$ (upper red line).

Since the aim of the aforementioned study was the identification of appropriate moments for automated lane changes [15, 16], no separate questionnaires about the longitudinal dynamic during passing maneuvers were used. However, the participants (P) had the opportunity to add qualitative comments on the assessment of their general sense of well-being and perceived discomfort, which can be used to investigate the suitability of the longitudinal dynamic. Several participants described the experienced longitudinal dynamic during lane changes qualitatively as too low (e. g. P5, P11, P19, P28, P39) and blocking rearward traffic in the target lane was mentioned several times as main reason for the perceived discomfort (e. g. P5, P19, P28, P39). For example, one participant (P19) described that such moderate lane changes would slow down rearward traffic and another participant (P39) suggested that rearward traffic would even expect a faster acceleration behavior of passing vehicles. Furthermore, another participant (P30) described that an additional benefit of higher longitudinal accelerations is the possible avoidance of safety-related aborts of automated lane changes that have already started.

In summary, various participants noticed the low longitudinal acceleration during automated lane changes in this study in a negative way and considered it uncooperative for rearward vehicles in the target lane. This influence of rearward traffic is examined in more detail in the following evaluation of non-automated lane changes, which represents the second step of this work (see Section 2).

4 Evaluation of Non-Automated Lane Changes

In addition to evaluating automated lane changes, we examined the longitudinal acceleration during non-automated lane changes in greater detail. For this purpose, the highD dataset [17] was used, which contains traffic records of several approximately 400 m long three-lane highway sections. The evaluation took into account lane changes to the left that were carried out in 38 highway sections with a maximum permitted speed of 120 km/h. This speed value corresponds to the target speed of the automation system described in Section 3 and thus contributes to the comparability of both data evaluations. As another prerequisite for consideration in this evaluation, the lane changes have to be completely included in the dataset and in the recorded highway sections. For this reason, referring to a previous data evaluation [15], each lane change was replaced by an individual logistic function (1) and the positions of the beginning and completion of the maneuvers were subsequently estimated. In this function, x_a represents the x-coordinate at which the lane markings are crossed by the respective recorded vehicle trajectory.

$$y(x) = \frac{G \cdot e^{k(x-x_a)}}{1 + e^{k(x-x_a)}} \qquad \text{with} \qquad y'(x_a) = \frac{G \cdot k}{4} \qquad \text{and} \qquad G = 3.75\,m \tag{1}$$

The beginnings of the lane changes were defined in accordance with the previous data evaluation [15] at the x-coordinates where the respective logistic functions reach 3% of the presumed lane width. In comparison, the completions of the lane changes were defined at the x-coordinates where the respective logistic functions reach 97% of the lane width. Fig. 2 shows as an example the first twelve of approximately 700 lane changes

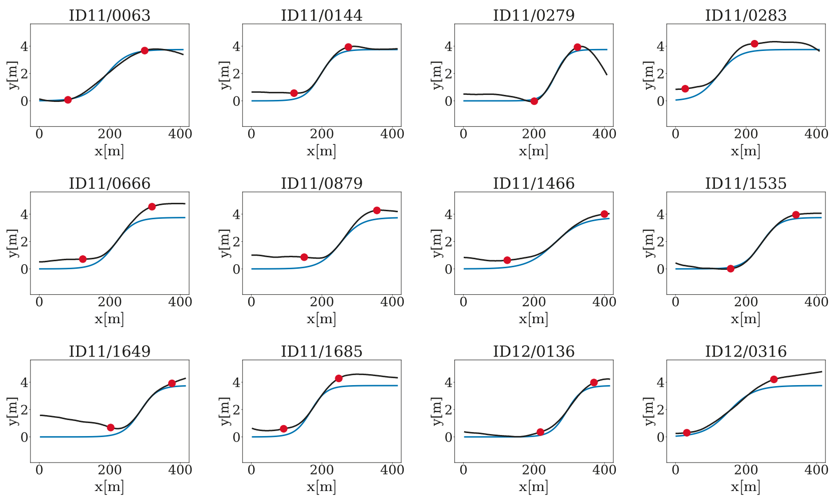

Figure 2: This figure shows the estimated positions of the beginnings and completions (red dots) of the first twelve non-automated lane changes considered in the data evaluation.

considered in this evaluation (black lines) with the logistic functions (blue lines) and the estimated positions of the beginnings and completions from a bird's eye view. Despite minor differences between recorded lane changes and the respective logistic functions, the calculated positions of the beginnings and completions are plausible and appear sufficient for our purpose.

For each lane change considered in this evaluation, the maximum longitudinal acceleration $a_{x,max}$ in the recorded highway section was identified and marked in relation to the difference Δv_x between the initial speed at the beginning of the lane change and the maximum permitted speed of 120 km/h in Fig. 3. In this process, a distinction was made between lane changes without and with a rearward vehicle in the target lane as well as between lane changes from the right lane to the center lane and from the center lane to the left lane. The relationship between the relative speed Δv_x and the maximum longitudinal acceleration was subsequently evaluated and with the help of linear regression functions (black lines) presented in Fig. 3. It can be seen that the longitudinal acceleration during lane changes from the center lane to the left lane are higher than the longitudinal acceleration during lane changes from the right lane to the center lane. This circumstance can be explained by the heterogeneous speed distribution on German highways [19] and the obligation to drive on the right-hand side of the road. Furthermore, it emerges that the longitudinal acceleration increases with the relative speed Δv_x and is slightly higher for lane changes with a rearward vehicle in the target lane ($\tilde{a}_{x,max} = 0.67$ m/s²) compared to lane changes without a rearward vehicle in the target lane ($\tilde{a}_{x,max} = 0.60$ m/s²).

In addition to Fig. 3, Fig. 4 shows lane changes with a rearward vehicle in the target lane including respective time-to-collision (TTC_x) values of the beginnings of the lane changes. The depicted gray surface represents the predictions resulting from a polynomial regression model. Here, an influence of the TTC_x on the maximum longitudinal acceleration during non-automated lane changes could not be identified.

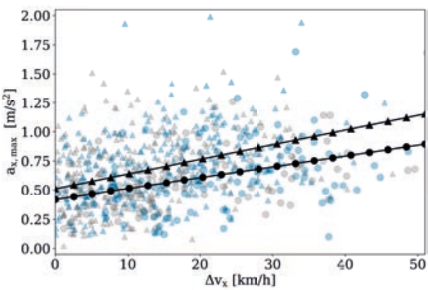

Figure 3: Maximum longitudinal accelerations during non-automated lane changes ($N = 713$) depending on the relative speed Δv_x. Dot symbols represent lane changes from the right to the center lane. Triangle symbols represent lane changes from the center lane to the left lane. Blue symbols represent lane changes with a rearward vehicle in the target lane. Gray symbols represent lane changes without a rearward vehicle in the target lane.

In summary, it can be stated that, from a descriptive point of view, the longitudinal dynamic during non-automated lane changes depends on the existence of a rearward vehicle in the target lane, the position of the lane change, and especially the relative speed Δv_x. At a high relative speed of 50 km/h, the maximum longitudinal acceleration during the driving maneuvers is approximately 1.2 m/s² on average. However, it should also be pointed out that there is a large scatter of maximum longitudinal accelerations during non-automated lane changes, which indicates additional influencing factors, such as individual human driving styles or personalities, and deserves further discussion.

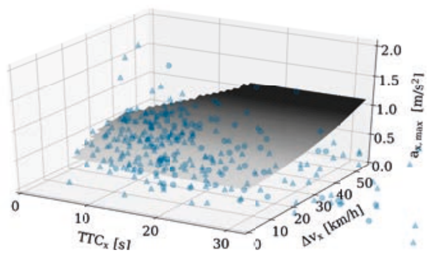

Figure 4: Maximum longitudinal accelerations during non-automated lane changes ($n_1 = 334$) with a rearward vehicle in the target lane depending on the relative speed Δv_x and TTC_x. Dot symbols represent lane changes from the right to the center lane. Triangle symbols represent lane changes from the center lane to the left lane.

5 Discussion and Conclusion

The longitudinal acceleration during automated lane changes assessed as too low in Section 3 and the longitudinal acceleration during non-automated lane changes investigated in Section 4 differ only to a minor extent ($a_{x,max} \approx 1.2\,m/s^2$). The assumption that the longitudinal acceleration during automated lane changes was designed too low in our last study is consequently not supported by the data evaluation of non-automated driving. However, we have to emphasize that the vehicle trajectories of the highD dataset [17] are only available in highway sections of about 400 m (see Fig. 2). It is conceivable that the actual maximum longitudinal accelerations are achieved before or after the evaluated non-automated lane changes and thus do not lie within the recorded highway sections. As a consequence, the actual maximum longitudinal accelerations would exceed the values presented in Section 4. In addition, various studies (e. g. [2, 6]) indicate that automated driving styles should not necessarily correspond to human driving styles. For this reason, the high degree of agreement between the automated longitudinal dynamics and non-automated longitudinal dynamics does not mean that increasing acceleration would not optimize driving comfort for automated driving. Taking into account previous research on automated driving, the qualitative participant opinions mentioned in Section 3, and the influence of rearward vehicles in the target lane on the longitudinal acceleration during non-automated lane changes (see Section 4), a maximum longitudinal acceleration during automated lane changes higher than $1.2\,m/s^2$ appears for individual traffic scenarios reasonable. Such scenarios include, for example, changes to faster lanes or lane changes in front of faster road users.

For future human-centered investigations of automated lane changes and in addition to the already known driving style with a maximum longitudinal acceleration of $1.2\,m/s^2$ described in Section 3, we recommend a driving style with a maximum longitudinal acceleration of $2.0\,m/s^2$. The latter value corresponds to the upper limit of adaptive cruise control systems [7] and is located in the lower range of a *dynamic* acceleration [4]. We hypothesize that such a dynamic acceleration during automated passing maneuvers reduce the perceived discomfort induced by blocking other traffic participants and consequently optimize the driving experience. For this reason, both mentioned driving styles were implemented in a prototypical vehicle, verified in a pre-study with experts under real-world conditions and will form the basis for a future study on the human-centered design of automated lane changes. With respect to higher levels of automated driving, which allow the driver to be distracted from traffic by non-driving related tasks [8], and the resulting impact on the human perception of driving dynamics [20], non-driving related tasks will be considered in our following study.

6 Acknowledgment

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