

Path Planning and Steering Control Concept for a Cooperative Lane Change Maneuver According to the H-Mode Concept

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Abstract—This article presents a concept for a possible implementation of the H-Mode (horse metaphor) concept in a test vehicle where the driver and the automation are simultaneously involved in the control loop of the driving task following the idea of shared control. Consequently, the driving task is executed as a cooperative collaboration between driver and automation. The developed concept is mainly focused on the cooperative shared lateral control of the driver and the automation during a lane change maneuver and consists of a combination of a path planning and a steering control concept.

I. INTRODUCTION

Currently, the research and development of driver assistance systems tends strongly towards automated driving. Supporting assistance systems for longitudinal and lateral vehicle guidance are already available in current series-production systems. These are for example adaptive cruise control [1] or lane keeping assistance systems [2].

One effect that comes along with high automation of the driving task is the drivers withdrawal from the driving task. In particular for partially automated driving [3] where the driver is still responsible for the driving task and in charge of monitoring the automation system of his vehicle, it is essential to keep the driver in the loop so that he can take over the driving task safely and in time at system boundaries [4]. A way to keep the driver in the loop is cooperative vehicle guidance following the idea of shared control [5]. Here, the driver can interact either event-discrete (Conduct-by-Wire, [6]) or continuously (H-Mode, [7]) with the automation system of his vehicle [8]. For the second case, the driver and the automation are simultaneously involved in the control loop of the driving task and try to realize their intended action by influencing the vehicle and each other [9].

Supporting the driver is especially important during cognitively high demanding maneuvers such as a lane change [10], [11]. This is why the presented concept is focused on a cooperative lane change maneuver which integrates into an existing concept for automated highway driving.

According to the interaction concept H-Mode, the lane change is realized with shared control of the driver and the automation (hands-on). In the presented article we consider the lateral vehicle guidance only. The longitudinal part of the driving task is performed by an existing adaptive cruise control system.

The article is structured as follows. Section two describes the fundamental theory and technical background behind the concept presented in this article. Based on these fundamentals, the concept for a cooperative lane change maneuver according to the H-Mode principle is developed in section three. Concluding, section four provides a summary and an outlook of the developed concept.

II. STATE OF THE ART

A. Cooperative vehicle guidance

In terms of developing driver assistance systems the automation level reflects the power of the automation system as well as the role of the driver or rather the availability of the driver in each automation level [12]. According to Flemisch et al. [13] the automation spectrum ranges from manual over assisted and semi automated to highly and fully automated vehicle guidance (figure 1).

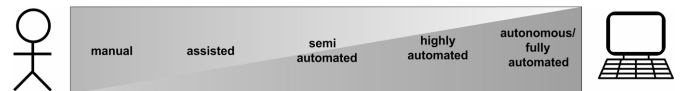


Fig. 1. Assistance and automation spectrum by Flemisch et al. [13]

The interaction concept for the cooperative automated lane change maneuver should show a preferably intuitive cooperation between driver and automation system. H-Mode is such a cooperative interaction concept [7]. Since driver assistance systems are increasingly intelligent and powerful, they can relieve the driver and influence the driver's actions. The influence of the automation system can contain varying automation levels. This can be defined according to the horse metaphor

as follows: if the rider mostly wants to have control he takes the reins firmly (tight rein). On the contrary, the rider can loosen the reins and consequently hand over control to the horse (loose rein). The horse can as well take over control in critical situations [14]. This concept can be transferred to automation or driver assistance systems: Tight and loose rein are according to the horse metaphor the automation levels “assisted” and “highly automated” (figure 1 and 2) [9].

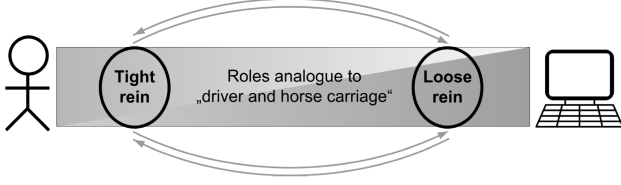


Fig. 2. Schematic representation of the tight/loose rein concept of the H-metaphor according to Flemisch et al. [7], taken from [13]

For the interaction concept H-Mode the driver and the automation are contemporaneously involved in the control loop of the driving task and try to realize their intended action by influencing the vehicle simultaneously and parallel [9], [12]. According to this, the vehicle guidance is a cooperative collaboration between driver and automation. Varying automation levels can be achieved by different weighting of the two cooperation partners and the transition should be as smooth as possible [15]. The communication and negotiation occurs primarily with haptic communication [9]. Thereby the gripping behavior on the control element, ideally an active actuator, could be used as an indicator of how much the driver wants to bring himself in the vehicle guidance [15]. The active actuator can generate forces as well which can be noticed by the driver and consequently ensure the haptic communication between driver and automation. The sum of the forces generated by the driver and the automation are passed to the vehicle.

B. Automation system and steering control

The driving task can be described by the three layer model by Donges [16]. It divides the task in the layers: navigation, path guidance and stabilization. On the guidance layer, the vehicle is guided by reference variables like target lane or target velocity. The task of the driver only consists of planning, whereas the actual realization takes place on the stabilization layer. On this layer the driver controls the proper motion of the vehicle in longitudinal and lateral direction via control elements to realize the position of the vehicle which was planned on the guidance layer [17], [12].

The cooperative lane change maneuver is an extension to an existing vehicle guidance concept which will shortly be described in the following (figure 3). The first module of the vehicle guidance system is the path planner which generates the path to get to the target state of the vehicle [18]. More detailed information for path planning will be presented in the following section II-C. The planned path and the current vehicle state is processed in a cascaded control loop which

consists of the path following and the steering angle controller. The path following controller is implemented as a PI-controller with feed forward control according to Kritayakirana et al. [19]. It internally determines the deviation of the current vehicle state from the desired state given by the planned path and calculates a target steering angle δ_{target} which is passed to the steering controller. The steering controller, a PID-controller with feed forward control, positions the steering system accordingly by commanding a steering torque $M_{S,target}$ via the torque interface of a standard electro-mechanical steering system. According to the three layer model by Donges, the path planner of the automation system is part of the guidance layer and the path following and steering angle controller are part of the stabilization layer.

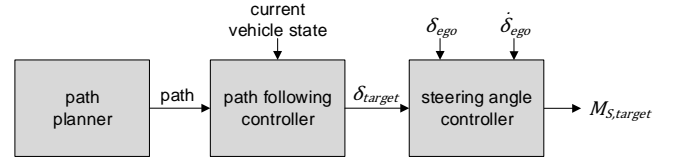


Fig. 3. Vehicle guidance concept

C. Path planning

The task of the path planning module is to plan a path from the start to the target configuration [18]. The presented article is based on the trajectory generation method by Werling [20] which uses a polynomial approach. Here, a trajectory is planned along a reference path in frenet coordinates. The target points vary in the available time for getting there and the lateral and longitudinal distance to the reference path. The lateral and longitudinal movements of the vehicle are considered independently so that there is an own polynomial for both moving directions. For a fifth-order polynomial the position, velocity and acceleration can be assigned in the starting d_0 and target point d_t respectively for lateral and longitudinal direction.

$$d_0 = \begin{pmatrix} s_0 \\ v_0 \\ a_0 \end{pmatrix}, d_t = \begin{pmatrix} s_t \\ v_t \\ a_t \end{pmatrix} \quad (1)$$

The optimality principle proves that in every point of the trajectory it is possible to generate a subsequent trajectory which has the current trajectory point as the start dynamic and proceeds the initial trajectory time consistent. This and further information for this approach on trajectory planning can be looked up in [20].

D. Research goal

The research goal of the presented article is to realize lateral vehicle guidance during a lane change maneuver with shared control between driver and automation (hands-on). The driver should get the possibility to influence the lane change path continuously and consequently the dynamic of the maneuver. Therefore, the lane change path should be adaptable based

on the driver's request. Moreover, the concept should as well include the recognition of the lane change intention of the driver during automated driving and the communication of a potentially not feasible lane change to the driver. According to the H-Mode, it is essential to realize an appropriate haptic feedback on the active actuator (steering wheel). Furthermore a transition between hands-on and hands-off driving should be possible anytime. For example a lane change started by the driver in shared control should be completed by the automation smoothly if the driver takes his hands from the steering wheel and thereby moves to the right bookend of the automation continuum.

III. CONCEPT COOPERATIVE LANE CHANGE MANEUVER

The cooperative lane change maneuver extends an existing concept for automated driving where the longitudinal vehicle guidance is always just performed by the automation. Furthermore, lane following is always realized with highly automated vehicle guidance. The concept itself will be presented in detail in the following according to the research goal (see section II-D).

A. Intention recognition for cooperative automated driving

Maneuver-based assistance systems support the driver on the guidance layer. Therefore, it is important to identify the lane change intention of the driver as part of the cooperative vehicle guidance. Parameters that are mentioned so far as indicators for a lane change intention of the driver are for example the increase of the glances in the side mirror, actuation of the brake pedal and throttle, indicator, distance and relative velocity to the vehicle ahead and distribution of the steering angle [10], [21]. Blaschke et al. [22] and Habenicht [17] developed a fuzzy-logic depending on several parameters which are mainly listed before. Summing up, all mentioned declarations are made based on manual driving.

Not all parameters listed in the paragraph before are suitable for identifying the lane change intention of the driver for the cooperative lane change maneuver because the maneuver follow lane is realized with highly automated driving. The steering wheel is the actuator for the interaction between driver and automation system according to the H-Mode concept, because of this parameters should be chosen to identify the lane change intention of the driver that are related to the steering wheel. Therefore, the threshold for the steering torque in combination with the indicator actuation are selected for identifying the beginning of the cooperative lane change maneuver. For the adaption of the lane change dynamics a combination of steering wheel torque and lateral deviation from the recently planned path is used.

If the driver for example wants to initiate a lane change to the right, he can do so by activating the indicator to the right and turning the steering wheel in the same direction with a certain amount of torque. Once the automation has recognized his intention it will plan a path to the right neighbor

lane and guide the vehicle along this path. If the driver now wants the lane change to be performed a bit more dynamically than initially planned, he can steer the vehicle away from the current path towards the target lane. The resulting steering torque and lateral deviation from the path leads to an adaption of the lane change path in the next planning step. If the driver releases the steering wheel again, the vehicle will continue on the adapted path. Contrary, if the driver wants a less dynamic lane change he has to steer the vehicle towards the left side of the path in case of a lane change to the right.

B. Controller behavior hands-on

Due to the fact that driver and automation operate the steering system simultaneously, it has to be analyzed how the existing controllers behave during hands-on operation. If the driver wants to drive systematically next to the target path, the P-component of the path following and steering angle controller generate a steering torque proportionally to the deviation to the path. Hence, the driver receives the desired haptic feedback that he is drifting away from the path and should orientate himself in the direction to the path. The I-components of the controllers guarantee stationary accuracy by increasing the actuating variable gradually by an existing control deviation. Therefore, slightest control deviation will be reduced [23]. During hands-on driving, the I-components of the path following and steering angle controller cause an increasing steering torque which forces the driver to return to the target path. This can possibly be incomprehensible for the driver because he can feel a comparatively high steering torque with just a minor deviation to the target path. Consequently, modifications to the two controllers are made while driving hands-on (figure 4).

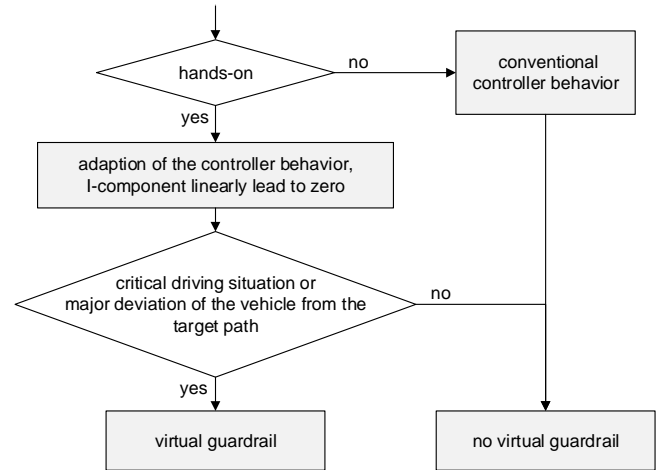


Fig. 4. Schematic representation of the controller behavior

To counteract this problem, the I-components of the path following and steering angle controller are linearly lead to zero with a limiting gradient after a successful hands-on detection. The I-components can resume their conventional behavior after the hands-off detection and a few milliseconds follow-up time.

The driver's request should be reduced or even prohibited in a potentially dangerous traffic situation or if a major deviation to the path is existent. This can be realized via a virtual guardrail with which the driver will get a limitation in the direction of his driving request. An example therefor is that the driver is driving beyond the target lane which should be prohibited to prevent a safety-critical situation. The virtual guardrail is realized with an additional torque according to a lane keeping assistance system [24] and the adaption of the steering assistance. The steering assistance is decreased with increasing deviation to the target path.

C. Adaptive path planning

The adaptive path planning should fulfill the following requirements for the cooperative lane change maneuver: Adaption of the lane change path according to the driver's request and prevention of safety-critical lane change situations. The adaption of the path for the cooperative lane change maneuver is realized by manipulating the starting and target point for the path planning algorithm (see section II-C). This includes the position, velocity and acceleration for the starting and target point in lateral and longitudinal vehicle direction for two fifth-order polynomials.

1) *Adaption of the starting point and dynamic:* The starting point can be chosen based on the current vehicle position and dynamic, the position and dynamic of the nearest path point of the not yet adapted path or as a combination of the two mentioned approaches before.

The selection of the starting point just from the current vehicle position and dynamic is not taken into account because there would not be any deviation between the vehicle and the planned path and thus no noticeable controller output as feedback for the driver. In contrast, the selection of the starting point only on basis of the nearest path point would theoretically be optimal because of the resulting steadily continued path. However this would also mean, that there is no adaption by the starting point at all. For this reason, this approach is not reasonable as well. Due to these mentioned factors, the starting point is chosen based on the current position and dynamic of the vehicle and the position and dynamic of the nearest path point of the not yet adapted path. This is illustrated in figure 5 for the position ($s_{0,x}$ and $s_{0,y}$) of the starting point. For the presented concept, the reference path is always the lane middle course of the target lane. The calculation of the starting velocity and acceleration in vehicle x- ($v_{0,x}$ and $a_{0,x}$) and y-direction ($v_{0,y}$ and $a_{0,y}$) occurs by the same schema and insists consequently partially on the current vehicle velocity and acceleration and partially on the dynamic of the path of the previous timestamp.

The following equation 2 specifies the calculation of the starting vector $\mathbf{d}_{0,x}$ in longitudinal direction which can similarly be applied to the lateral vehicle direction ($\mathbf{d}_{0,y}$). The weighting of both parts results from the parameter f_{ego} which

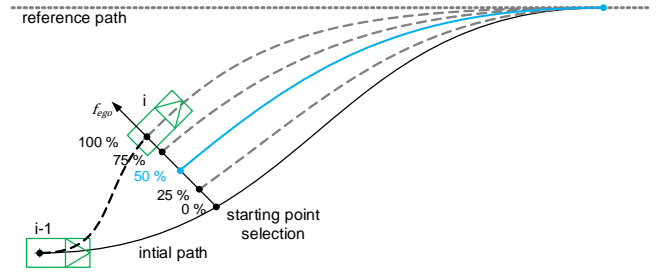


Fig. 5. Graphical representation of the calculation of the adaptive path's starting point with the parameter $f_{ego} = 0,5$

reflects the percentage weighting of the vehicle position and dynamic.

$$\mathbf{d}_{0,x} = \begin{pmatrix} s_{0,x} \\ v_{0,x} \\ a_{0,x} \end{pmatrix} = \begin{pmatrix} s_{ego,x} \\ v_{ego,x} \\ a_{ego,x} \end{pmatrix} \cdot f_{ego} + \begin{pmatrix} s_{p,x} \\ v_{p,x} \\ a_{p,x} \end{pmatrix} \cdot (1 - f_{ego}) \quad (2)$$

The selection of the starting point during hands-off driving occurs just on basis of the nearest path point.

2) *Selection of the planning time and target point:* The selection of the target vectors in lateral and longitudinal ($\mathbf{d}_{t,x}$ and $\mathbf{d}_{t,y}$) direction is rather trivial because of assuming a constant longitudinal velocity and a lateral velocity and acceleration equal to zero. Consequently, the longitudinal position s_x is the result of the current longitudinal velocity multiplied with the planning time τ (time between the current and the target point of the path). The middle course of the target lane is the reference path with the initiation of the lane change maneuver. Therefore, the lateral starting position is approximately 3,5 m and the lateral target position is 0 m.

$$\mathbf{d}_{t,y} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}; \mathbf{d}_{t,x} = \begin{pmatrix} v_x \cdot \tau \\ v_x \\ 0 \end{pmatrix} \quad (3)$$

The selection of the planning time is important because of the characteristic behavior of fifth-order polynomials, that leads to an overshooting of the resulting path (see figure 6) for certain planning times. Heil [25] formed equations to counteract this problem by calculating a planning time interval that guarantees a not overshooting path. More information to this approach can be found in [25].

The lane change (LC) maneuver begins with a predefined initial lane change time. The calculation of the remaining lane change time $\tau_{adapt,i}$ for the current timestamp i is based on the planning time $\tau_{LC,i-1}$ of the previous timestamp. The planning time is at each timestamp reduced by the cycle time $\Delta\tau_{i-1,i}$ if no cooperative selection of the starting point is existent. This means that the time for completing the lane change maneuver is absolutely constant. In contrast to that, the planning time for cooperative selection of the starting point is adapted based on the driver's request by what the completing

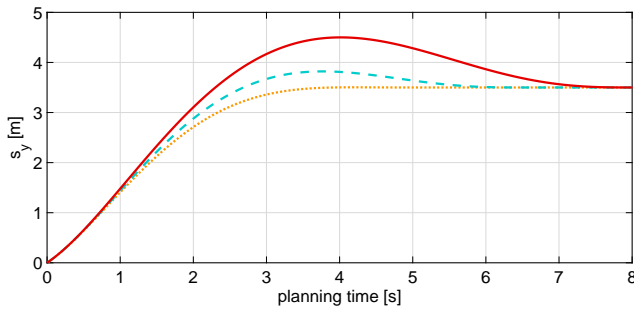


Fig. 6. Lateral position of different paths with varying planning time $\tau = \{5; 6,5; 8\}$, lateral starting dynamic $d_{0,y} = [0 \ 1 \ 1,5]^T$ and lateral target dynamic $d_{t,y} = [3,5 \ 0 \ 0]^T$

lane change maneuver time is varied. As mentioned in section III-A the deviation to the target path is used as the intention recognition of the driver's request regarding the lane change dynamic. The deviation $d_{y,p}$ has therefore, multiplied with an weighting parameter $f_{LC,\tau}$, an influence on the calculation of the planning time. Accordingly, the remaining lane change time is reduced if the driver steers towards a more dynamic path (see figure 7) or increased if the driver steers towards a less dynamic path.

$$\tau_{adapt,i} = \tau_{LC,i-1} - \Delta\tau_{i-1,i} + d_{y,p} \cdot f_{LC,\tau} \quad (4)$$

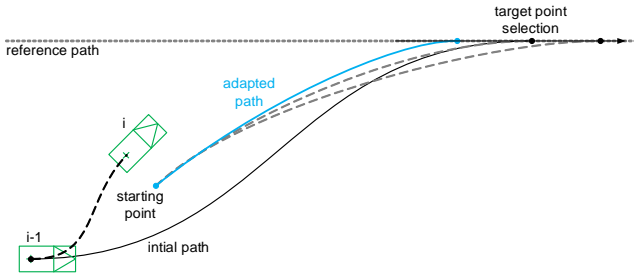


Fig. 7. Graphical representation of the calculation of the adaptive path's target point with the parameter $f_{ego} = 0,5$

Concluding, the remaining lane change time has to be compared to the critical overshooting time according to the equations mentioned before and the smaller one has to be chosen to prevent overshooting of the path.

3) *Structural flow of the path planning and examination of the dynamic constraints:* The simplified structural flow of the path planning for one timestamp is presented in figure 8. First, there is only an adaption of the starting point if the case hands-on driving is active. Following, the planning time is calculated. The starting position of the path planning and the lane change time directly influence the lateral dynamic of the lane change path. In order to avoid too dynamic lane change situations the lateral acceleration and jerk are limited. This is realized by restricting the minimum remaining lane change time. Moreover, overshooting of the path should be prevented

as well by limiting the maximum remaining lane change time $\tau_{LC,i}$ with the critical overshooting planning time $\tau_{overshoot,i}$ (equation 5).

$$\tau_{LC,i} = \min \{ \max \{ \tau_{adapt,i}, \tau_{dyn,i} \}, \tau_{overshoot,i} \} \quad (5)$$

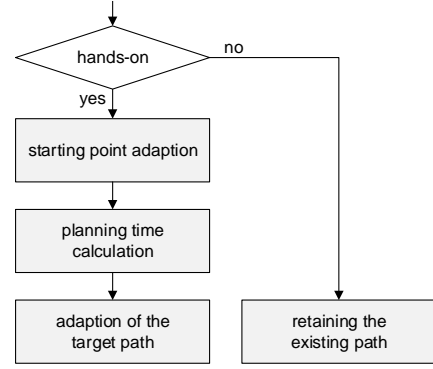


Fig. 8. Structural flow of the path planning for the cooperative lane change maneuver

D. Connection between adaptive path planning and controller behavior

A connection or interaction between adaptive path planning and controller behavior is necessary to impede or even prohibit the driver's request and according to this prevent a potentially dangerous traffic situation. The recognition of the traffic situation is part of the path planning and the haptic feedback for the driver at the steering wheel is realized with the steering controller for which reason the interaction is essential.

A virtual guardrail is implemented in order to prevent the driver from overshooting the reference path. The virtual guardrail (orange) is on the dynamic lane change side and is activated from a predefined lateral distance to the reference path while approaching the reference path. Thus, the driver's request for a more dynamic lane change should be decreased and the driver should get a haptic feedback in the direction of the target path (figure 9). Moreover, another threshold for the lateral distance to the reference path is implemented which is according to the amount smaller and is aimed to guide the driver to the middle course of the target lane (red). Consequently, the driver receives a haptic feedback on both sides of the path and no cooperative starting point selection occurs.

A similar connection between path planning and controller behavior occurs if it is required to reject a lane change request of the driver for a potentially dangerous traffic situation (figure 10) like a potential collision object in the neighbor lane. The decision if the lane change is safe or not is taken for granted and not part of the presented concept. If it is not safe to change lanes, the driver receives a virtual guardrail to the side with the

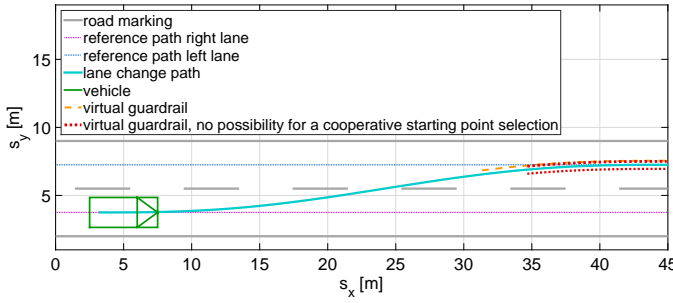


Fig. 9. Characteristics of the controller and the path planning at the end of the lane change maneuver; initial lane change time $\tau_{LC,init} = 5$ s and vehicle velocity $v_x = 30$ km/h

impedance to realize a haptic feedback to prohibit the lane change intention. Moreover, the lane change maneuver can not be initiated in this situation for which reason the maneuver follow lane is continued.

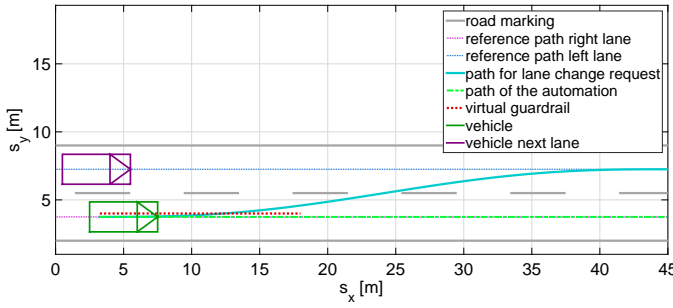


Fig. 10. Characteristics of the controller and the path planning while restraining the driver's lane change request

The virtual guardrail is realized as a combination of an additional steering torque and reducing the steering assistance as mentioned in section III-B.

IV. CONCLUSION AND OUTLOOK

A concept for a cooperative automated lane change maneuver according to the H-Mode concept was presented in this article. The driver can thereby completely hand over the lateral vehicle guidance to the automation while lane changing or perform the lateral vehicle guidance as shared control. Nevertheless, the lane change maneuver has always to be initiated by the driver. This concept includes the recognition of the lane change maneuver during automated driving, the communication of a potentially not feasible lane change maneuver to the driver and the shared control for the lane change maneuver. Thereby, the driver has the possibility to influence the dynamic of the lane change within uncritical constraints. This is realized as a combination of adaptive path planning and a developed controller behavior for the case hands-on. The shared control is implemented with haptic feedback for the driver at the steering wheel (active actuator) to influence the driver's requests and guide the driver through the lane change maneuver to avoid safety-critical situations.

Moreover, a harmonic transition between the two cases hands-on and hands-off is realized.

The presented concept has been tested on a proving ground with velocities up to 70 km/h. For the future, the concept will be transferred to an automated highway driving system to evaluate it with higher velocities and in real driving conditions. Furthermore, the path planning should be optimized because Sporrer et al. [26] identified an asymmetric lane change characteristic for manual driving which would reflect the real driving behavior more appropriate. In addition to that the concept has to be extended by integrating the longitudinal part of the vehicle guidance in the future.

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