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Combining haptic human-machine interaction with predictive path planning for lane-keeping and collision avoidance systems

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Abstract— **This paper presents a first approach for a haptic human-machine interface combined with a novel lane-keeping and collision-avoidance assistance system approach, as well as the results of a first exploration study with human test drivers. The assistance system approach is based on a potential field predictive path planning algorithm that incorporates the drivers wishes commanded by the steering wheel angle, the brake pedal or throttle, and the intended maneuver. For the design of the haptic human-machine interface the assistance torque characteristic at the handwheel is shaped and the path planning parameters are held constant. In the exploration, both driving data as well as questionnaires are evaluated. The results show good acceptance for the lane-keeping assistance while the collision avoidance assistance needs to be improved.**

I. INTRODUCTION

One of the key issues in bringing advanced driver assistance systems (ADAS) like lane-keeping, lane-changing or collision avoidance systems into the market is the design of an appropriate interaction between driver and driver assistance systems. The driver acceptance depends on a thorough driver and situation based design of the human-machine interface.

There is a significant amount of research on lane-keeping and collision-avoidance, see [1], [2] for an overview. There also exist approaches, combining lane-keeping and collision avoidance, see e.g. [3], [4] or [5]. Besides this more control oriented research, there is also a large amount of research in designing the human-machine interfaces (HMI) for ADAS. An overview about the design of haptic HMI is given in [6]. In [7] an active steering-wheel is compared with a side-stick both for force-feedback characteristics with and without a threshold. For an active steering-wheel a force-feedback characteristic with a threshold is preferred. The work of [8] was one of the first, combining both active steering and vibrations for haptic warnings. Haptic and acoustic warnings in lane-keeping assistance where compared in [9]. It turned out that, if the acoustic warning can distinctly assigned to a lane-departure, it results in lower reaction time compared to a haptic warning. In [10] a steer-by-wire system is used to combine the steering command of a virtual driver with the steering command of the driver for lane-keeping assistance. Testing on a fixed-based driving simulator reveals an inverse relation between the driver acceptance of this approach to the virtual driver's influence. A handwheel force-feedback design approach for a steer-by-wire system combined with a potential field based lanekeeping controller is proposed in [11]. Stability issues are considered with respect to the feedback of inertia, damping and aligning moment to the handwheel. The lane-keeping system investigated in [12] uses an HMI where the steering-wheel assistant torque is scaled with the deviation between desired and actual steering-wheel angle. It is shown that with lane-keeping assistance the average lateral deviation from the lane is smaller than without lane-keeping assistance and that the haptic feedback reduced the visual workload of the drivers. The haptic HMI of the Honda lane-keeping system is investigated in [13]. A permanent steering torque intervention is proposed for lane-keeping, where the assistant torque is shaped with respect to the lateral deviation of the vehicle from the lane center. The level of assistance the test drivers prefer is 80 %, which means that the 20 % of the necessary torque for lane-keeping shall come from the driver. The evaluation further reveals an increase in comfort without retraction of the driver from the driving task.

In [14] the process of sharing responsibility between a human driver and a collision avoidance system as a trade off between safety enhancement and human autonomy is considered. Therein, the predicted safety enhancement must be compelling enough to justify the cost to the drivers autonomy.

There are several important issues in designing haptic human-machine interfaces for lane-keeping and collision avoidance assistance. Among them are the balance between comfort and safety. A lane-keeping assistance system shall reduce the driver's workload by simultaneously guaranteeing that the driver will not withdraw completely from the driving task, see [13]. How to communicate different driving situations like lane departure or collision avoidance is another important issue to be addressed. For collision avoidance situations there are investigations, which show that drivers may react in the wrong way to haptic communications, see [9], [15]. Also differences in the situation awareness and interpretation between driver and machine may result in driving intention conflicts.

This paper presents the combination of handwheel force-feedback with a potential field path planning and path following approach for lane-keeping and collision avoidance assistance. The driver can influence the path planning by the haptic interaction with the vehicle. The haptic HMI can be shaped by the parameters of the assistance torque characteristic and the path guidance is tuned by the path planning parameters. We address the question whether the

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proposed approach results in safer vehicle guidance with respect to critical driving situations than without assistance. The proposed approach is a first step towards a haptic communication where lane-keeping and collision avoidance assistance are presented via the same information channel. To keep things simple, a linear force-feedback characteristic is chosen, depending on the deviation between the desired and the actual handwheel steering angle. The exploration with human test drivers shall provide information about the applicability of the proposed approach, the driver acceptance, comfort and safety awareness and indications on how to shape the assistant-torque characteristic and the path planning.

II. Assistance system structure

In Fig. 1 the control structure of the lane-keeping and collision avoidance assistance system is shown. The driver assumes control over the longitudinal vehicle guidance, whereas driver and assistance system work cooperatively for the lateral vehicle guidance. At the planning instant t_0 both handwheel torque, T_{driver}, as well as throttle and brake pedal forces, F_{f}, are fed to the control system. The actual handwheel steering angle, ρ_{w} and powertrain output, $T_{\mathrm{d/b}}$, are the control inputs to the vehicle. The path planning module adapts to the driver's commands via the vehicle states ${}_{R}\mathbf{q} = [{}_{R}x^{CG}, {}_{R}y^{CG}, \chi]$, ${}_{V}\mathbf{v} = [v_x, v_y, \dot{\chi}]$, as illustrated in Fig. 4, the vehicle acceleration ${}_{V}\mathbf{a}$ and the actual steering angle δ. A replanning of the path is carried out at time

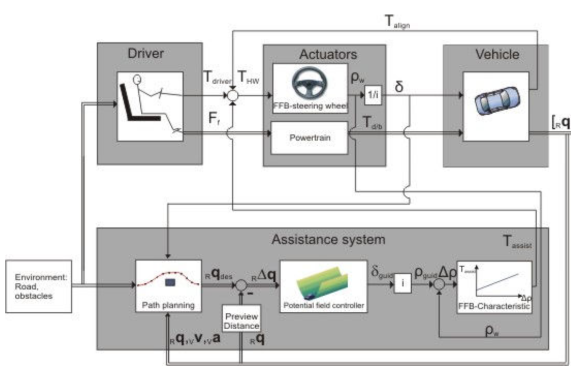
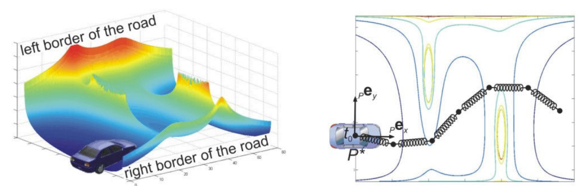


Fig. 1. Assistance system control structure

intervals of ΔT to adapt to environmental changes and changes in the driver's commands. The controller acts on the configuration level, regulating the position and heading deviation between the desired vehicle configuration, given by ${}_{R}\mathbf{q}_{\mathrm{des}} = [{}_{R}x^{T*}, {}_{R}y^{T*}, \chi_{\mathrm{des}}]$, and the actual vehicle configuration at the preview distance l_{PV}, given by ${}_{R}\mathbf{q} = [{}_{R}x^{CG} + l_{PV}\cos\chi, {}_{R}y^{CG} + l_{PV}\sin\chi, \chi]$. Without driver commands, the potential field controller guide the vehicle along the predicted path via its steering angle output δ_{guid}. With the driver in the loop, a shared control approach is chosen, guaranteeing that the driver is kept in response to the overall vehicle guidance. This is realized by feeding the driver's handwheel steering command, ρ_w directly to the vehicle. The haptic interface between the driver and the vehicle is adjusted by an assistant-torque characteristic depending on the difference between the actual handwheel steering angle ρ_{w} and the handwheel steering angle ρ_{guid} necessary to follow the planned path. To override the commanded handwheel steering angle from the potential field controller, ρ_{guid}, the driver must however overcome the assistance torque T_{assist}. To recreate an accustomed handwheel steering feel it is necessary to provide the aligning torque T_{align} at the handwheel. Inertia effects of the steering system are not considered for handwheel feedback here. Their influence on the stability of the vehicle in combination with a potential field lanekeeping controller is investigated in [11].

A. Path Planning

The potential field path planning approach combining both lane-keeping and collision-avoidance for autonomous driving is described in detail in [5] and [16]. The two basic elements are shown in Fig. 2. A potential field hazard map is generated from from the environmental sensor data by assigning repelling potential fields to the borders of the road and to moving or non-moving obstacles. The path finding



(a) Hazard map (b) Elastic band

Fig. 2. Potential field path planning elements

within the hazard potential is carried out by a so-called elastic band, consisting of nodes connected by linear elastic springs. Immersing the elastic band in the hazard potential causes external forces onto the nodes of the elastic band, shifting the elastic band towards regions of low hazard into an equilibrium configuration. For a global search of a drivable path either several elastic bands can be chosen passing all detected obstacles on their left and right side or, only one elastic band is taken but a hazard algorithm is used that shows the elastic band a starting path for the search. In case where several elastic bands are chosen, after finding all equilibrium points the best path must be selected by using drivability criteria such as the maximum lateral curvature for example. Without obstacles, the potential field of the borders of the road are shaped so that the equilibrium position of the elastic band is in the mid of the lane, thus describing the path for the lane-keeping mode.

In the collision-avoidance mode, this path planning approach is spatial and temporal predictive. It is assumed that at the planning instant t_0 position, orientation, speed and acceleration of the host vehicle are known. Based on the initial speed and acceleration of the host vehicle at time t_0 its trajectory is extrapolated along the elastic band giving $[{}_{R}x^{CG}(t), {}_{R}y^{CG}(t)]$. Also, it is assumed that the environmental sensors detect position, orientation, velocity, yaw rate and acceleration of all obstacles at the planning time t_0. Thus, also the obstacles trajectories are extrapolated. Similar to the borders of the road, the obstacles are modeled by repulsive potential fields. The idea of incorporating moving obstacles in the path planning approach is now that the moving potential field $V^{O_j}(t)$ of the obstacle O_j shall act only on those nodes of the elastic band, which correspond to the same instant of time t. In this sense, the path planning is spatial and temporal predictive.

B. Cooperative Path Planning

In subsection A the idea for path planning without driver inputs was sketched. Now, for a cooperative driving between the driver and the path planning module, three basic interfaces are introduced, drivers steering intention, braking or acceleration intention and maneuver intention. Using a non-holonomic single-track vehicle model, an extrapolated path is generated at the planning instant t_0, depending on the actual steering angle δ, see Fig. 3 and Fig. 1. The relative position of the first n nodes of the new elastic band are determined from this extrapolated path. The drivers

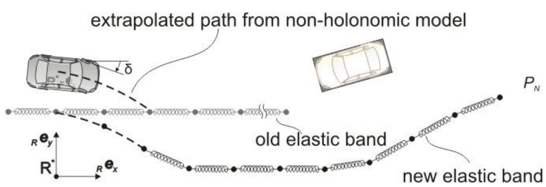


Fig. 3. Influencing the path planning with the steering angle

braking or accelerating intention is incorporated into the path planning by extrapolating the host vehicle's motion along the elastic band with the given acceleration $a(t_0)$ at the planing instant t_0. The drivers maneuver intention like lane-changing is assigned to the position of the last node P_N. In case the driver sets the turn signal, the last node is positioned at the center of the neighboring lane.

C. Path Following Controller

After a path $\mathcal{P}$ is planned the host vehicle shall follow this path. Therefore, a guidance controller is designed as illustrated in Fig. 4. The controller input ${}_R\Delta\mathbf{q}$ in Fig. 1 is computed from the guidance deviation between the preview point PV and the corresponding point $T*$ on the path $\mathcal{P}$. Based on [17], the controller computes an artificial force in lateral vehicle direction ${}_VF_{\mathrm{guid_y}} = -k_{\mathrm{lat}}\ {}_T\Delta y^{PV} \cos\Delta\chi$, as shown in Fig. 4, that is transformed in a corresponding steering angle input, see [17] Eq. (32), $\delta_{\mathrm{guid}} = {}_VF_{\mathrm{guid_y}}/C_\alpha^F$ using a planar one-track model, with C_α^F being the cornering stiffness at the front tire. Here, constant speed of the vehicle is assumed.

D. Assistance Torque Characteristics

The block of the force-feedback characteristic in Fig. 1 uses the difference between the handwheel steering angle ρ_{guid} as input, commanded from the guidance controller and the actual handwheel steering angle ρ_{w}. If the driver follows

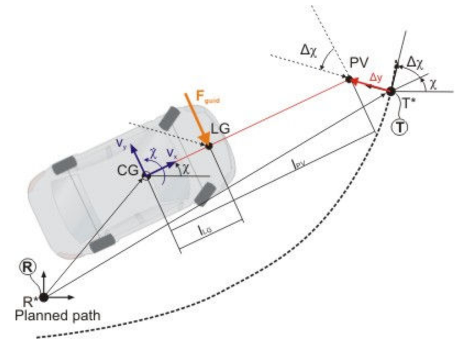
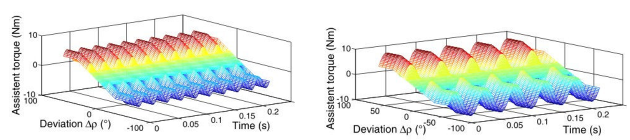


Fig. 4. Vehicle guidance controller

exactly the commanded handwheel steering angle ρ_{guid}, no assistance torque T_{assist} is generated and the driver has only to overcome the aligning torque T_{align} as it is in an vehicle without lane-keeping assistance. If the driver deviates from the desired handwheel steering angle an assistant torque is applied. To keep this first user study simple, linear characteristics with a saturation treshold have been chosen. Other more sophisticated characteristics are considered e.g. in [13] and [7] p.58. Two kinds of assistant-torque characteristics are distinguished depending on the driving mode, a lane-keeping characteristic and a collision-avoidance characteristic, as depicted in Fig. 5. The design parameters as well as the chosen values are given in Tab. I. They have been obtained by a preliminary user study. In this small study the users were asked about how convenient or adequate different settings are. The task of the assistance torque characteristic is splitted



(a) Lane keeping mode (b) Collision avoidance mode

Fig. 5. Assistance torque characteristics for different driving modes

into two subtasks: path tracking and path departure warning. For path tracking an assistant torque intervention without treshold is chosen. The path departure warning is activated beyond a handwheel steering angle deviation of $\pm 15^o$ and superpose a sinusoidal warning torque. The threshold may be speed dependent. However, this is not considered here, as the user studies where carried out at constant vehicle speed. The difference of the lane-keeping mode and the collision avoidance mode is in the frequency and the amplitude of the sinusoidal assistant torque. In case an obstacle is detected, then the assistance system switches from the lane-keeping characteristic to the collision avoidance characteristic.

III. Driving Simulator

A fixed based driving simulator has been build to test and design the proposed path planning algorithm, the corresponding path following controller and the assistant torque characteristics. In Fig. 6 the driving simulator is shown. The hardware components are a force-feedback wheel, a brake pedal and throttle, three beamers, three screens and three PC's (each a Dualprocessor-computer with 3.2 GHz and 2 GB RAM) connected via ethernet. The vehicle is modeled

Fig. 6. Driving Simulator

with three lateral degrees of freedom and one degree of freedom for each wheel. A virtual sensor has been programmed, which detects the borders of the road and obstacles on the road. This virtual sensor emulates the environmental sensors of the vehicle. All software components where integrated into a simulation software [18], which is a C++ library together with a shared memory for data exchange. Each software module has access to the shared memory and can take information from it as well as write information into it. In Fig. 7 an example situation with two obstacles on the road is depicted.

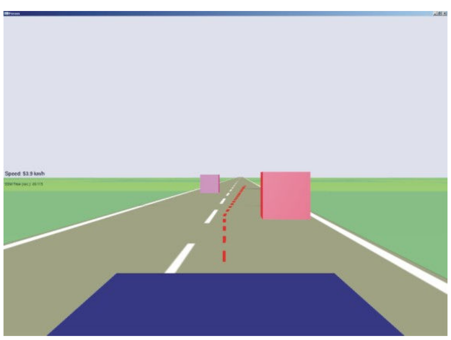


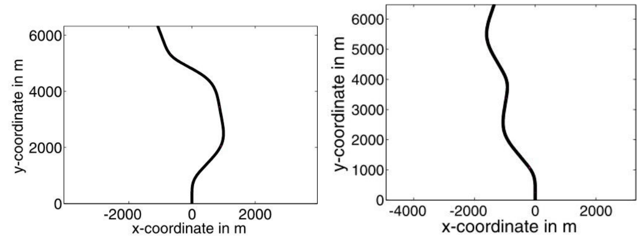
Fig. 7. Road with obstacles

IV. First exploration

In this first exploration the focus is on the acceptance of the assistance system and on the evaluation of two different designs of the assistant torque characteristic. In the first subsection, the design of the exploration is described and in the second subsection the objective and subjective evaluation criteria are formulated.

A. Exploration Design

The main task of the test drivers for the exploration is to drive along a curved road with a speed of 100 km/h. Two different courses are chosen, as depicted in Fig. 8. Each course has an approximate length of 6 km and the driving time is approximately 4 minutes. Along a course



(a) Course 1 (b) Course 2

Fig. 8. Road courses for the exploration

4 non-moving obstacles will suddenly pop up on the road at different locations and at different distances in front of the host vehicle. In normal driving situations drivers are sometimes distracted from the driving task. This can happen for example when setting the navigation system or searching for a radio canal. To incorporate the influence of visual awareness of the driver during the test drive, a secondary task is defined. The drivers have to search in a picture with letters on a monitor for those letters different from the letter T. Two different assistant torque characteristics are chosen for the exploration. A soft and a hard assistant variant. Both differ from each other by the slope of the assistance torque characteristic $T_{\text{assist}}(\Delta\rho)$, see Fig. 5. The slope parameters for soft and hard assistance are given in Tab. I. Also the vibration parameters for lane-departure warning and hazard warning are stated in this table. With the courses, the settings

	SOFT ASSISTANCE	HARD ASSISTANCE
Lane-keeping torque		
scaling	$1\frac{Nm}{rad}$	$8\frac{Nm}{rad}$
saturation	±5Nm	±5Nm
Lane-departure warning		
frequency	40Hz	40Hz
amplitude	2Nm	2Nm
treshold	±15	±15
Hazard warning		
frequency	20Hz	20Hz
amplitude	5Nm	5Nm
treshold	±15	±15

TABLE I

Parameters of the soft and hard assistant torque

for the assistance torque characteristics as well as the description of the secondary tasks, the basic design parameters to evaluate the human-machine interface are formulated. A test scenario consist of the combination of an assistant torque characteristic, a secondary task and a course. In Tab. II six different test scenarios are defined. In order to counterbalance the exploration four test sequences are defined with the test scenarios. Each test driver is randomly assigned to one of these four test sequences. The sequences are stated in Tab. III. Before the test drives are carried out each test driver learns to handle the vehicle in the simulator by driving along

No.	Test Scenario	Abbreviation
1	no assistance/no secondary task/course 1	nA/nT/1
2	no assistance/with secondary task/course 1	nA/sT/1
3	hard assistance/no secondary task/course 1	hA/nT/1
4	hard assistance/with secondary task/course 2	hA/sT/2
5	soft assistance/no secondary task/course 2	sA/nT/2
6	soft assistance/with secondary task/course 2	sA/sT/2

TABLE II

Definition of test scenarios

sequence 1	sequence 2	sequence 3	sequence 4
nA/nT/1	nA/nT/1	nA/nT/1	nA/nT/1
nA/sT/1	nA/sT/1	nA/sT/1	nA/sT/1
sA/nT/2	hA/nT/1	hA/sT/2	sA/sT/2
sA/sT/2	hA/sT/2	hA/nT/1	sA/nT/2
hA/nT/1	sA/nT/2	sA/sT/2	hA/sT/2
hA/sT/2	sA/sT/2	sA/nT/2	hA/nT/1

TABLE III

Test Sequences

a training course, which is different from the test courses. The test drivers will practice also the secondary task, both without driving and with driving. There is no time limit to accustom to the vehicle handling and to learn the secondary task. However, the training is without the pop up of obstacles. For the exploration 16 test drivers are taken, half of them male. Eight of the drivers where under 35 years old. The age is between 18 and 60 years. The driving experience of the drivers ranges from beginners up to drivers with a large driving experience.

B. Evaluation criteria

To evaluate the haptic human-machine interface both objective as well as subjective criteria are used. As objective criteria driving quantities are chosen, specifically the averaged deviation from the planned path and the number of collisions with the non-moving obstacles. During the test drives many driving data such as the vehicles yaw rate, the vehicle speed, or the assistance torque are logged to ensure that both the assistance system and the driving simulator work properly. A questionnaire was compiled to evaluate the subjective impression of the drivers after each test scenario. The questionnaire did not base on a template. Also there were no previous works on that in our group. It was classified in several parts. There were questions about the improvement of the haptic human-machine interface design, including the strength of the vibrations and the threshold at which the vibrations shall begin. The drivers should give their impression about the assistance system, e.g. wether they felt an assistance. Also the level of assistance should be evaluated graded from paternalism up to a reduced driving workload. It was asked about additional warnings like acoustic or visual warnings. And last, the general acceptance of such an assistance system should be evaluated with respect to safety and comfort.

V. Results

For the evaluation of the haptic human-machine interface driving data and data extracted form a questionnaire are chosen.

A. Evaluation of Driving Data

The two criteria for an objective evaluation are the averaged deviation from the planned path and the number of collisions with the non-moving obstacles. In Fig. 9 the six test scenarios, defined in Tab. II, are compared. The figure

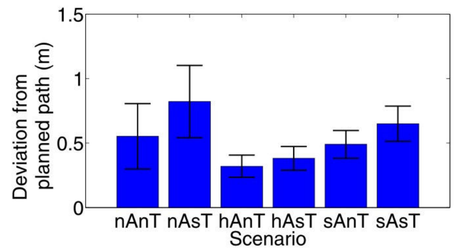


Fig. 9. Averaged deviation from the planned path

reveals that the deviation from the planned path is larger for the test scenarios with secondary task. Furthermore it is remarkable that the driving performance increases under the hard type of the assistant torque. The test scenario without assistance and without secondary task (nAnT) results in a larger deviation compared to the test scenario composed of the hard assistance with secondary task (hAsT). Figure 10 visualizes the difference in driving with the lane-keeping system and the collision avoidance system. In all test drives

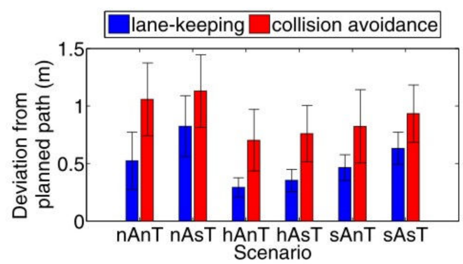


Fig. 10. Comparison between lane-keeping and collision-avoidance

the lateral deviation to the planned path is significantly smaller while driving with the lane-keeping system. Having a look onto the driven path of each test driver, indicates, that they lie closely together. Whereas in the collision avoidance system differences in the time of leaving the own lane, keeping the distance with regard to the obstacle and returning to the own lane occur.

Another important rating factor for evaluating the collision avoidance system is the number of actual accidents, as summarized in Table IV. First, the number of collisions is an indicator for the drivers work load when solving the secondary task. Second, the number of collisions correlated with the type of assistance (no assistance, soft assistance, hard assistance), can indicate effects of the level of assistance. The table shows, that the number of collisions is significantly reduced with increasing level of assistance. However, it has to be clarified in further studies why without a secondary task the soft assistance can introduce a collision and why at

	without secondary Task	with secondary Task
without assistance	0	19
soft assistance	2	6
hard assistance	0	4

TABLE IV

NUMBERS OF COLLISIONS

all collisions occur with the hard assistance. One explanation could be that the haptic assistance is misinterpreted by the driver.

B. Evaluation of Questionnaire

The values of the subjective evaluation criteria partially align with the values of the objective criteria. Many test drivers state that the lane-keeping assistance system reduces their work load when solving the secondary task. However, for collision-avoidance maneuvers the test drivers did not experience an improvement by the collision-avoidance assistance system. The different assistance levels are rated as improvable as can be seen in Fig. 11. Despite the good

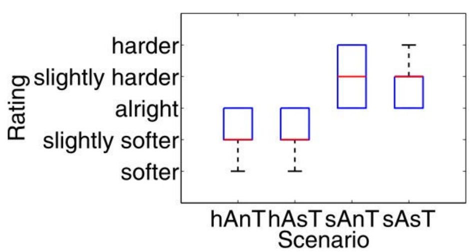


Fig. 11. Rating of collision-avoidance intervention

performance with respect to the objective criteria in Fig. 9 and Tab. IV, the confidence of the test drivers into the collision-avoidance system is rated between medium and good. Another point of interest are additional warnings for example acoustic or visual warnings. Also, showing the planned path could be a further step to guide the driver during a collision avoidance maneuver.

VI. CONCLUSIONS AND FUTURE WORKS

With the evaluation of a haptic human-machine interface combined with a novel lane-keeping and collision-avoidance system a first step towards a proof of the concept has been demonstrated. The predictive potential field path planning algorithm worked and the combination with a haptic human-machine interface showed evidence for a good lane-keeping performance and an reduction of the number of collisions. The proposed system is rated as a expedient system with respect to comfort and safety by the test drivers.

Improvements in the design of the collision-avoidance system are most important. For example the distance ahead of an obstacle until the system intervenes for the take-over is not satisfying. Also the turn back to the original lane needs to be tuned. These are changes which have to be made within the path planning algorithm. Also improvements in the haptic interaction with the driver can be investigated. It is for example important to deal with conflicts in the situation awareness and interpretation between driver and machine and their successive driving intention. Other important aspects for future research will be the integration of moving obstacles and moving traffic in the evaluation and the incorporation of emergency braking maneuvers in the path planning. Another future aspect is to investigate the influence of the steering system inertia and damping in the handwheel force-feedback both for stability reasons and for the HMI design.

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