Driver-in-the-Loop Simulation for Advanced Driver Assistance Systems

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A hardware-in-the-loop (HIL) simulation of an advanced driver assistance system (ADAS) for adaptive front lighting was coupled to a driving simulator with a reconfigurable motion platform and a high-performance visualization system to integrate human drivers into the closed control loop. This combination leads to a driver-in-the-loop (DIL) simulation. In contrast to vehicle control systems, for which HIL simulations are sufficient to ensure correct functionalities, ADA systems require such a DIL approach because they support human drivers rather than directly taking action in vehicle stabilization. With DIL simulation, it is possible to ensure that an ADA system is functioning correctly and test its acceptance by the human driver on a simulator during the development phase.

Active safety and driver assistance system; modeling and simulations; state estimation

1. INTRODUCTION

The development and testing of advanced driver assistance systems (ADAS) such as collision avoidance systems, lane change assistance systems, or adaptive front lighting systems, can be supported by simulation configurations to reduce research and development costs dramatically. However, unlike classic vehicle control systems, ADA systems address human drivers, supporting them in controlling their vehicles rather than directly taking action in vehicle stabilization. Thus, human drivers play an important role in developing and testing ADAS controllers. This paper describes a simulation configuration that takes this into account: To perform driver-in-the-loop (DIL) simulation, a hardware-in-the-loop (HIL) simulation of an ADAS controller for adaptive front lighting is extended by a driving simulator featuring a 5-DoF motion platform carrying a vehicle with human-machine interface (HMI) and a complex animation system, in order to include the human driver in the closed control loop. This combination is essential to assess the quality of the functionalities of the electronic control unit (ECU), which requires a realistic visualization of the road illumination during a night drive, based on a specific headlamp model. A multitude of different night drive scenarios can be simulated thoroughly with such a simulator setup to test whether other road users are subjected to glare, e.g., in oncoming vehicles approaching behind a hill or vehicles coming from the side at junctions or bridges.

This paper focuses on the HIL simulation part of the overall DIL simulation configuration, and it especially details the functionalities of the headlamp control module (HCM; the specific ADAS ECU used in this DIL simulation setup) and the approach to front light modulation, the implemented simulation layout, and the additional environment modeling needed for the closed-loop simulation.

The DIL simulation of the adaptive front lighting is part of the TRAFFIS research project, funded by the European Union and the government of North-Rhine Westphalia (Germany) and carried out by a combination of academic and industrial project partners [1].

2. DIL SIMULATION OVERVIEW

Fig. 1 gives an overview of the simulation setup. For the DIL simulation, a driving simulator with a reconfigurable 5-DoF motion system is used, on which different test vehicles can be operated. The system generates the vehicle motion via a combined approach with two different actuator types: The base platform performs a coupled rotational/translational movement in longitudinal and lateral direction for large amplitudes, and a 3-DoF shaker mounted on the base platform imposes additional vibrations and small-amplitude motions on the vehicle, see also [2,3].

For the animation of the environment and the light distribution of the headlamps during a night drive, a high-performance 8-channel rendering and projection system is with a 240° visualization range is used. In addition, an acoustic module and animated cockpit elements generate a realistic perception of driving.

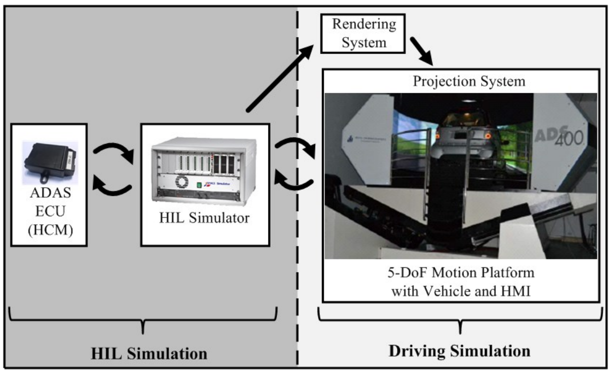

Fig. 1 DIL simulation overview

The HCM for adaptive front lighting serves as the device under test for the HIL simulation, which is part of the DIL simulation setup. The HIL simulator uses vehicle dynamics and environment models to calculate the controller inputs, i.e., vehicle states, camera data, and electronic horizon data, in real-time. The headlamp control signals from the HCM are received by the HIL simulator and are sent to the rendering system together with vehicle states and environment signals. With the underlying headlamp model it is possible to generate a realistic illumination of the road that takes into account the current traffic, the driving situation and the actuator signals sent by the HCM.

The HIL simulator is used to control the motion platform of the driving simulator by solving motion cueing algorithms. These algorithms take the kinematics of the motion platform into account and use the current vehicle states resulting from the vehicle dynamics models to control the inverters for the actuators of the driving simulator.

By coupling a classic HIL simulation with a driving simulator like this, it is possible to integrate human drivers into the closed-control loop of the device under test. Thus the functionalities of the ECU and acceptance by drivers can be examined thoroughly on the simulator.

3. HEADLAMP CONTROL MODULE (HCM)

Today's high-end front lighting systems adapt the beam pattern of the headlamps to current and upcoming road and traffic scenarios to improve safety and also to increase driving comfort by giving the driver an optimum of visibility. Such systems contain an ECU that listens to vehicle or other sensor signals (from a navigation system, camera system, etc.) on a CAN bus and controls headlamps via CAN or LIN to switch light sources and drive actuators. Fig. 2 gives an overview of the electrical architecture of the HCM used in the TRAFFIS research project. Two separate LIN buses were chosen to keep the system modular and extendable for additional actuators. Due to the mounting positions of the headlamps within the crash zone of the vehicle, an architecture with at least 2 different communication lines is necessary.

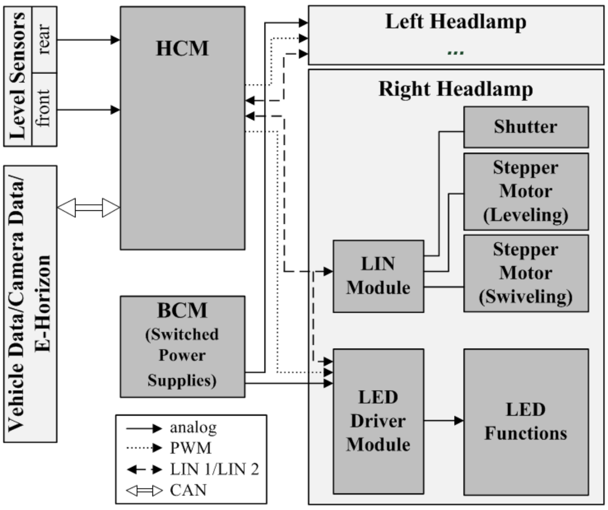

Fig. 2 Electrical architecture of the HCM

To achieve optimum front light performance, two different front lighting ADAS functionalities were combined in the TRAFFIS research project: a camera-based glare-free high beam (GFHB) system and the e-horizon-based predictive adaptive front lighting System (PAFS).

3.1 Glare-Free High Beam (GFHB)

The GFHB system is a high beam assistance system that increases high beam time to provide maximum road illumination. A camera system detects the traffic situation (oncoming and preceding vehicles) and transmits the geometric characteristics (distances, angles, etc.) of the traffic location (U-frame) to the HCM. The HCM controls special GFHB headlamp modules to avoid glare for road users by generating an adaptive dark spot or shadow area, cf. Fig. 3. According to the object area (left, center or right in front of the ego-vehicle) a beam shape setup is chosen. The shadow area can be moved horizontally or vertically within a reasonable range by leveling or swiveling actuators in the headlamps to follow the traffic objects' area position.

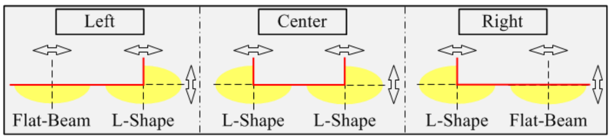

Fig. 3 Beam shape setup for left, center and right traffic object area position

Various headlamp technologies such as halogen, HID, LED or laser light sources are possible. A combination of 3 LED light sources with beam patterns switchable by shutter technology was chosen for the TRAFFIS project. This guarantees a good and homogeneous beam pattern setup to generate a standard low beam, a flat beam, a high beam or an L-shape beam; Fig. 4 and Table 1 give an overview of the strategy for light modulation.

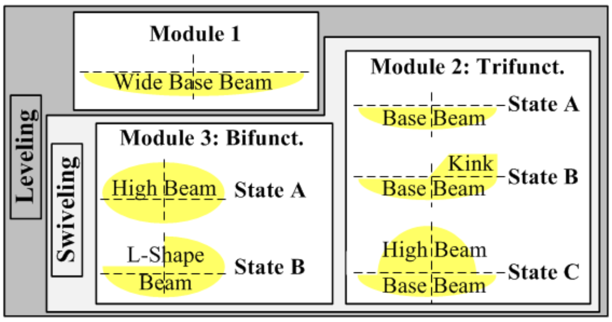

Fig. 4 Headlamp modules and functions

Table 1 Strategy for beam shape modulation

Beam Shape	Module 1	Module 2	Module 3
Low Beam	on	State B	off
High Beam	on	State C	State A
Flat Beam	on	State A	off
L-Shape	on	State A	State B

A combination of L-shape (left and/or right) and flat beams makes it possible to generate the shadow area mentioned above to avoid glaring.

The GFHB system's performance is mainly driven by the camera system. Delays, wrong object detection or non-detection will directly lead to weak behavior. Optimized adaptive filtering has to be applied to achieve the best result (e.g., if an object is detected, lost, and redetected, or with discontinuous output data like U-frame borders or object distance).

3.2 Predictive Adaptive Front Lighting System (PAFS)

The predictive adaptive front lighting system uses an e-horizon (digital map data within a most likely path (MLP) defined by various map attributes) to adapt the beam pattern to road geometry (3-D shape), road scenarios (roundabouts, intersections, branching, etc.) and road classes (play street, urban, rural or highway) or country code information (EU/UK – right-/left-side traffic). When this information is known, the beam pattern can be adapted to illuminate the road geometry and scenarios in advance by means of leveling and swiveling actuators. The driver is better prepared for upcoming road scenarios.

The PAFS performance is mainly driven by the e-horizon. Out-of-date maps with lower accuracy (especially on minor roads, e.g., small country roads) or map errors due to road changes or bad data collection will affect behavior directly. Moreover, very accurate geometrical road reconstruction by appropriate interpolation strategies, high-performance map matching and perfect selection of the most likely path are essential characteristics of a good working e-horizon. Within the PAFS it is absolutely necessary to detect e-horizon-based issues in advance so that the controller can fall back on conventional AFS control.

3.3 GFHB-PAFS Combination

Combining GFHB and PAFS optimizes the advantages of both systems by merging data from all the available sensors, and removes the limitations that apply if only one of them is available. Every conceivable item of data from the vehicle, including the driver, traffic and road, is now available. Moreover, sensor data can be checked for plausibility, and possible map errors can be directly detected by means of camera and vehicle data. Additional data otherwise not available can be used to confirm functionality (e.g. automatic country setting or road class provided by a map with higher validity). An adaptive and situation-based selection to generate the best combination of lighting control strategies defines the final system. This makes the system more robust, leading to enhanced visibility and a safer and less stressful driving experience.

4. HIL SIMULATION

The control loop of the implemented HIL simulation with the HCM is illustrated in Fig. 5, where the different grayscales mark the transition between modeled parts and real parts. The HCM serves as the device under test and sends control signals to the headlamp actuators. In this simulation layout, real actuators are used for the leveling and swiveling motion of the headlamps' projection modules.

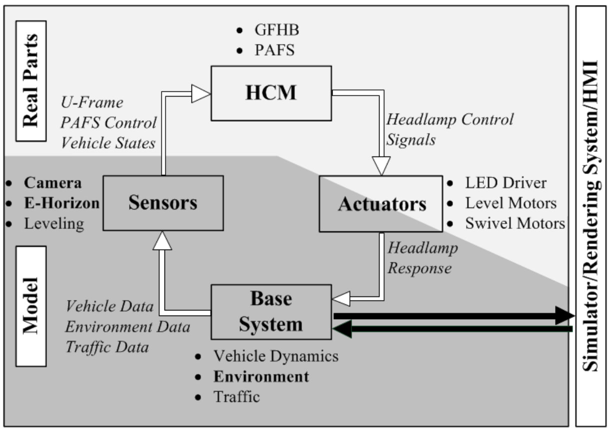

Fig. 5 HIL simulation overview

The base system, describing the dynamics of a passenger car as well as the environment and traffic, receives the response signals from the actuators and serves as the interface to the motion platform of the simulator, the rendering system and the HMI. The simulated sensors generate the signals needed by the real HCM and thus close the control loop.

One general difference between ADAS controllers and vehicle dynamics controllers is that they get their input signals from more complex sensor devices, e.g., camera systems, electronic horizons, or Car2x communication. Thus for ADAS HIL simulations it is essential to simulate the sensor devices and also to have an appropriate environment model that can stimulate these sensors.

In the next sections, the model modifications necessary to realize the HIL simulation for the ADAS controller are presented in detail.

4.1 Environment Model for ADAS Applications

The Automotive Simulation Models (ASM) by dSPACE serve as base models for the HIL simulation, see also [4]. Fig. 6 illustrates the differences between the environment models for vehicle dynamics (a) and for ADAS applications (b). For vehicle dynamics it is enough to have an environment model that can simulate vehicle dynamics use cases, e.g., ABS brake, µ-split brake, fishhook maneuvers or following paths on handling tracks. For ADAS use cases, on the other hand, additional characteristics of the environment model have to be taken into account; the most important aspect being the transition from a vehicle dynamics proving ground or a handling track to a complex road network consisting of multiple instances of roads and intersections.

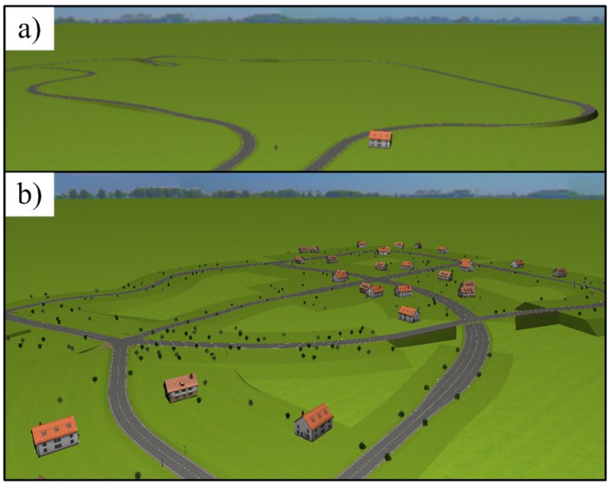

Fig. 6 Environment model for vehicle dynamics (a) and ADAS (b) applications

An environment model capable of simulating use cases for ADAS applications and based on an environment model for vehicle dynamics simulations was therefore developed for the TRAFFIS project. This new environment model is able to handle multiple instances of road objects and also includes intersection objects to connect the road instances and create a complex road network, cf. Fig. 6 (b). The standard options which can be used to describe a road for vehicle dynamics applications have been kept: the definition of xy, height and lateral slope profiles, the definition of additional surface conditions and frictions, etc. It is also possible to define additional road characteristics that are important for different ADAS applications, e.g., lanes, lane transitions, line types and colors, additional road textures, and road scenery objects.

The intersection objects can be defined with an arbitrary number of roads connected to them, and the intersection surface and profile can be designed freely by using a unique definition for the intersection area.

With these options for defining an intersection, most of the intersections and side road layouts occurring in reality can be modeled. Nevertheless, especially in an urban setting, there might also be more complex intersection layouts that cannot be handled by a single intersection object. Some examples are intersections with special side roads, roundabouts, or highway entrances and exits. However, in these cases the generic network approach can be used to model such complex layouts by using multiple instances of road and intersection objects, cf. Fig. 7 showing an example of a highway interchange (a green dot marks a connection between an intersection and a road).

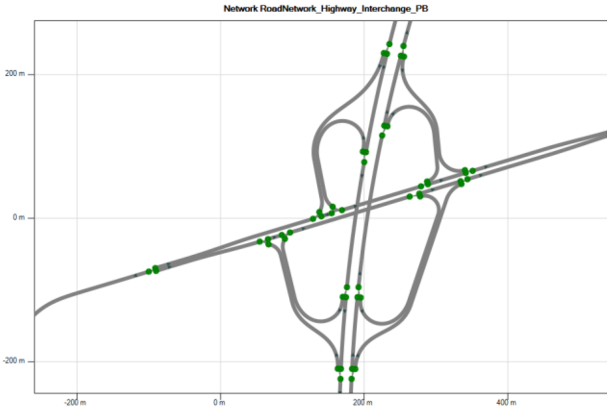

Fig. 7 Road network model for a highway interchange

4.2 Camera Simulation

The GFHB functionality of the ADAS controller needs U-frame data as input signals; the U-frame is visualized in Fig. 8 (b).

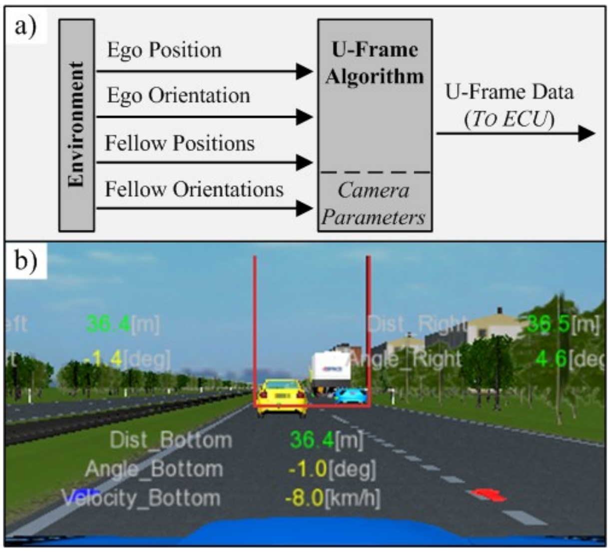

Fig. 8 Structure of the camera simulation (a), animated U-Frame (b)

In a real vehicle these signals are sent by a camera that observes the area in front of it. Complex image processing algorithms analyze the traffic situation and among other things calculate the geometric values for the area in which fellow vehicles are located and glare must be avoided. For HIL simulation, the U-frame data needed by the HCM is simulated by an implemented U-frame algorithm, which gets the position and orientation data on the ego-vehicle and the other fellow vehicles that are near to the ego-vehicle from the environment model, which has been adapted for ADAS applications.

The algorithm can be adapted by tuning the camera parameters: the position of the camera in the vehicle, the horizontal and vertical opening angles, etc.

4.3 E-Horizon/PAFS Simulation

The HCM needs data from an electronic horizon for the predictive front lighting functionality PAFS. The position of the ego-vehicle and the most likely path are therefore calculated by the newly developed environment model as GPS data; Fig. 9 (b) illustrates the MLP of the ego-vehicle by means of a series of shape points in front of the vehicle.

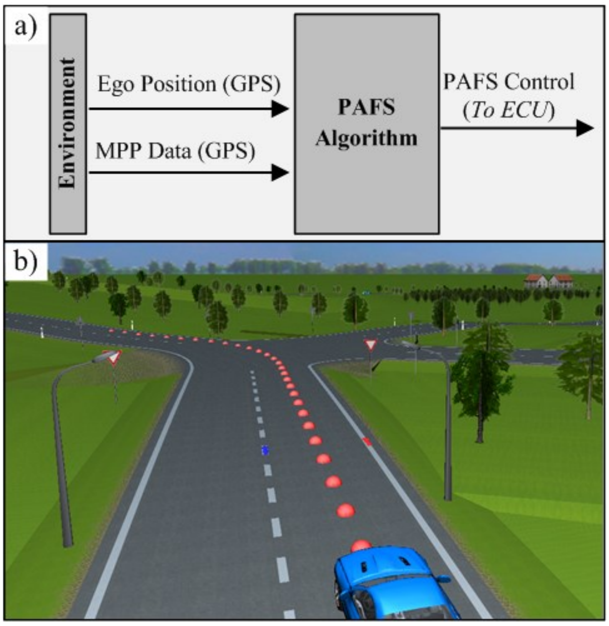

Fig. 9 Structure of the e-horizon simulation (a); animated MLP (b)

Using the GPS data, a PAFS algorithm implemented in the simulation model calculates target values for the headlamp actuators. These signals are sent to the ADAS controller so that it can adapt the light distribution even before the driver performs actions, e.g., via the steering wheel, acceleration or brake pedal, or changes in driving behavior occur. The controller has to combine the information from the camera and the electronic horizon, which is often contradictory, to determine the optimal illumination of the road in front of the vehicle, while at the same time avoiding glare for other fellow vehicles.

5. RESULTS

Some example results of the camera simulation are shown in Fig. 10.

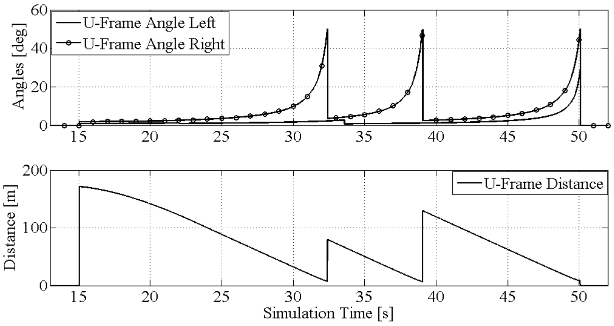

Fig. 10 Results of camera simulation

To demonstrate the characteristic behavior of the U-frame, the example uses a simulation scenario in which the ego-vehicle overtakes three vehicles driving in the right lane of a straight highway section. All the vehicles drive at a constant velocity and there are no lane changes. The upper plot in Fig. 10 shows the angles from the ego-vehicle's center to the side limits of the U-frame, displayed in an ego-vehicle-fixed reference system (positive: right side of the ego-vehicle, negative: left side of the ego-vehicle). Because the vehicles are passed on the ego-vehicle's right side, the angles of the U-frame are both positive for this simulation scenario. At each simulation time t1 = 32s, t2 = 39s and t3 = 50s, the ego-vehicle comes so close to another vehicle that it disappears out of range of the camera. Until the second vehicle disappears out of view, there is always more than one vehicle enclosed by the U-frame. This also becomes apparent in the behavior of the U-frame's side angles: In the first time period (delta_t = 15s-39s) where the ego-vehicle passes the first two vehicles, the left and right U-frame angles diverge, i.e., the U-frame spans a wider area to enclose more than one vehicle. During the second time period (delta_t = 39s-50s), the differences between the left and the right U-frame angles are smaller, because the U-frame encloses only one vehicle. The lower plot in Fig. 10 shows the distance from the ego-vehicle to the U-frame during the simulation scenario.

Fig. 11 shows example simulation results illustrating the PAFS algorithm, which generates input signals for the ADAS controller. In this simulation scenario the ego-vehicle follows the course of a curvy road and the algorithm sends control signals to the controller before the vehicle reaches a corner. The upper plot of Fig. 11 shows the vehicle velocity [kph]; the other plots display the curves of the steering wheel angle ([deg]; middle plot) and the control signals for the swivel angles of the left and right headlamps ([deg]; lower plot). Comparing the curves of the swivel angles to the steering wheel reveals that the control signals to set swivel angles for the headlamps are manipulated even before the steering wheel angle changes. This shows the predictive adaptation of the headlamp actuators based on the knowledge of the most likely path, i.e., the shape of the road in front of the vehicle.

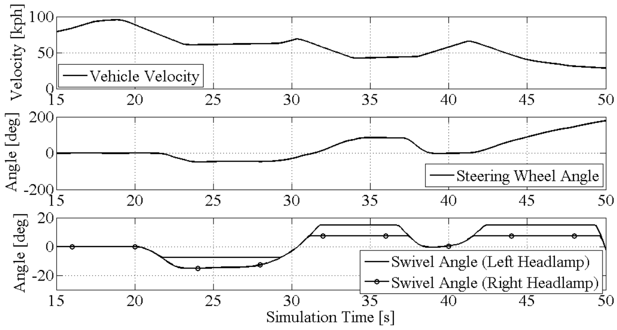

Fig. 11 Results of e-horizon simulation

The HIL simulation of the HCM is just one part of the whole DIL simulation setup. For the evaluation of the controller's functionalities by human drivers, it is essential to have a rendering and projection system that is able to convert the controller signals into a realistic illumination of the road and other traffic vehicles. Fig. 12 shows images of a night drive scene in original colors and in false colors, which can be visualized on the projection system on the driving simulator.

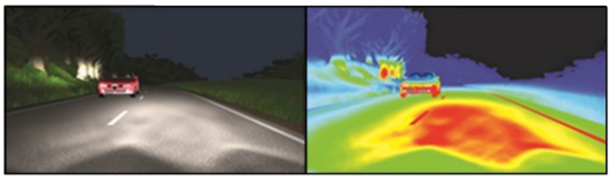

Fig. 12 Example of a night drive scenario

The characteristics of the headlamps are defined exactly by a combination of measured and calculated distributions of luminosity, and can be rendered in real time. For more information about the visualization of headlamps during night drives, see [5, 6].

The 240° projection system covers the human driver's peripheral vision to give a realistic impression of GFHB and PAFS, and the controller's functionalities can be tested and evaluated under various driving scenarios.

6. CONCLUSION

This paper presents a DIL simulation environment for developing and testing ADAS controllers that was built for the TRAFFIS research project. For the DIL simulation, a HIL simulation of an ADAS controller for adaptive front lighting (headlamp control module, HCM) is coupled to a reconfigurable driving simulator consisting of a 5-DoF motion platform, an HMI and an 8-channel 240° projection system. Depending on the control signals for the headlamp actuators generated by the real HCM, the rendering system calculates the light distribution and generates a realistic animation of the illuminated environment during night drives. Thus it is possible for human drivers to evaluate the ADAS functionalities under realistic driving conditions in the laboratory.

A Headlamp Control Module for adaptive front lighting from Varroc, one of the project partners, is used as the device under test. The HCM combines one camera-based ADAS functionality for a glare-free high beam and one e-horizon-based predictive, adaptive front lighting system. The headlamp strategy used for the light beam shape makes use of three LED light sources, shutter technology, and horizontal and vertical stepper motors.

The HIL simulation uses a combined approach of vehicle simulation and real headlamp actuators. The simulation of the controller's input signals differs from well-established vehicle dynamics simulation in that other types of sensor signals have to be provided, i.e., camera and electronic horizon signals. Major model modifications have to be implemented for this. In general, ADA systems support the driver mainly in coping with situations where other road users are involved, so it is important to have an environment model that is able to simulate such driving situations. The environment model presented here therefore allows the modeling of complex road networks, e.g., for urban simulation scenarios. In addition, model modifications to provide the camera and electronic horizon signals needed by the controller are also presented.

Results from the camera simulation and the simulation of the electronic horizon, in combination with example images of a night drive scene, illustrate the characteristics of the model adaptations and give an insight into the possibilities for evaluating the ADAS functionalities provided by the complete DIL simulation.

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