USING LARGE MOVING BASE SIMULATORS AS TOOLS WHEN DESIGNING DRIVING AUTOMATION FOR COMMERCIAL HEAVY VEHICLES
A CASE STUDY OF HIGHWAY AUTO-PILOT FOR HIGH CAPACITY TRANSPORT

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Abstract

This work aimed at analysing the potential for the application of large driving simulators on the study of future automated driving functionality. The case study was centred on applications for heavy vehicles, focusing on lane-change manoeuvres and automated driving. A simulation environment was created which hosted a model of a real world road, motion emulation with high fidelity truck dynamics, controllable surrounding traffic and a driver assistance system including autonomous driving. Two types of heavy vehicles were selected for this study, an 80ton and 32m long A-Double combination vehicle and a 40ton and 20m tractor semi-trailer. The final experimental set-up was driven by a group of professional truck drivers. It was concluded that today's resources in terms of hardware, software and even knowledge base satisfy the requirements for testing such automated systems in a holistic way. Driving simulators are capable of providing much valued feedback as well as insight at early stages of function design which can effectively speed up, focus and streamline further development.

Keywords: High Capacity Transport, Driver Assistance, Driving Automation, Driving Simulation

1. Introduction

High Capacity Transport (HCT) is currently under increased consideration for freight transport given its potential to yield relevant productivity gains (Working Group on Heavy Vehicles: Regulatory, Operational and Productivity Improvements, 2009). Among others, this type of transportation has the potential to improve fuel efficiency and reduce emissions and is even considered to have equivalent or even better safety characteristics (dynamic stability) than their conventional counterparts (Working Group on Heavy Vehicles: Regulatory, Operational and Productivity Improvements, 2009). However, the increased weight and length of HCT rises questions over other safety topics such as potential aggravation of consequences in case of accidents, safety under overtaking manoeuvres and impact on the traffic flow. (Working Group on Heavy Vehicles: Regulatory, Operational and Productivity Improvements, 2009). A better understanding of these issues is a necessity as HCT become more common on the road networks.

Automated driving functionalities and driver assistance systems are a rising trend within contemporary vehicle development. Their rate of development, shear diversity, and often implications on vehicle control and stability place pressure on testing and validation procedures. Testing tools and methodology need to adapt to the ever increasing demands of these new systems (Fischer, M, 2014).

Due to their flexibility, driving simulators open up testing possibilities in transport related areas from study of the impacts of new transportation to testing of automated functionality, among many others. Research examples emerge with increasing frequency within evaluation of automated driving functionalities and driver assistance systems while using driving simulators. Given the broad and varied nature of such functions, this can imply a rather high workload in terms of simulation set-up just to answer the needs of specific interfaces for different systems. This further motivates the need of increased adaptability from a driving simulator in terms of hardware and/or software (Fischer, M, 2014). By developing a simulation architecture which is independent of the tested vehicular system, it is possible for different actors to share testing functionality while retaining the same simulator interface, thus reducing testing times and increasing interoperability. In this work, a simulator architecture is tested and presented as an example of a solution to integrate external automated driving functionalities in a simulator environment.

An experiment was conducted to compare the characteristics of manual and automated driving during lane-change manoeuvres of HCT under simulated traffic conditions. An assistance function, SAE level 3 automation (SAE J3016 Jan 2014), designed to aid the driver with such manoeuvres was under scrutiny. This work focuses on the possibility to use driving simulators as a complementary testing tool for commercial heavy vehicles, thus the aim is to describe the process, considerations and lessons learned from implementing and conducting said experiment, from a simulator perspective. Detailed analysis of the autonomous functionality as well as the driver lane-change manoeuvre performance are not within the scope of this work and will be addressed in future publications.

2. Case Study

Studies have shown that lane-change/merging manoeuvres yield a high frequency of accidents involving today's heavy vehicles (Sandin, J. 2015), (Blower and Kostyniuk 2007). A detailed analysis of Swedish crash databases revealed that the great majority of these incidents occur when changing to the right lane while a vehicle is concealed on the truck's blind spot [12]. Moreover, the same study has also reported that the majority of lane-change manoeuvre related crashes occur on multi-lane highways passing through larger cities. Standard heavy vehicles have many similarities with HCT thus, it is legitimate to assume that these types of accidents will carry over to the latter. In speculation, it is even possible to assume that HCT can increase the risk of such accidents due to longer lengths and increased weight, properties which affect vehicle handling.

To mitigate the risks involved in a lane-change manoeuvre one could consider a system which automates this procedure. The latter would collect information about road network, traffic conditions as well as vehicle states and use it to perform a lane-change manoeuvre at the request of the driver.

This case study was designed with two goals in mind. Firstly, to study the feasibility of such automated functions from the algorithms' layout, their interaction with the truck and finally the drivers' impression of the system performance. Secondly, to collect data on how drivers execute lane-change manoeuvres while driving heavy vehicles without any support functions.

The case study consisted of driving sessions with and without the assistance system, SAE level 3 of automation, or conditional automation (SAE J3016 Jan 2014). The test subjects drove standard and non-standard (HCT) heavy vehicles on a multi-lane road modelled after a real world network in the city of Gothenburg, Sweden. Surrounding vehicles were modelled to generate similar traffic conditions to the ones found in a realistic lane-change situation. All driving tests were performed with SimIV, the latest moving base driving simulator of the Swedish National Road and Transport Research Institute (VTI), (Jansson et al, 2014).

3. Simulation Architecture

Definition of a balanced simulation architecture is an essential step to ensure an even distribution of available computational resources. It is important to understand the needs of the different tasks as well as their correlations before settling for the final layout. The structure used in this case study is depicted in figure 1.

The simulation kernel consists of an application developed by VTI which is responsible for the management of the driving simulation. The software ensures communication between all simulation units and hosts the processes which manage the driving scenarios experienced by the test subjects. The road network module is responsible for accurate placement of traffic as well as event triggering. Surrounding traffic simulation selects and actuates different control strategies for the vehicles surrounding the truck, creating realistic driving conditions. Finally, motion cueing regulates the motion platform in such a way that its displacements resemble those of a truck, further contributing to the driver feeling of immersion.
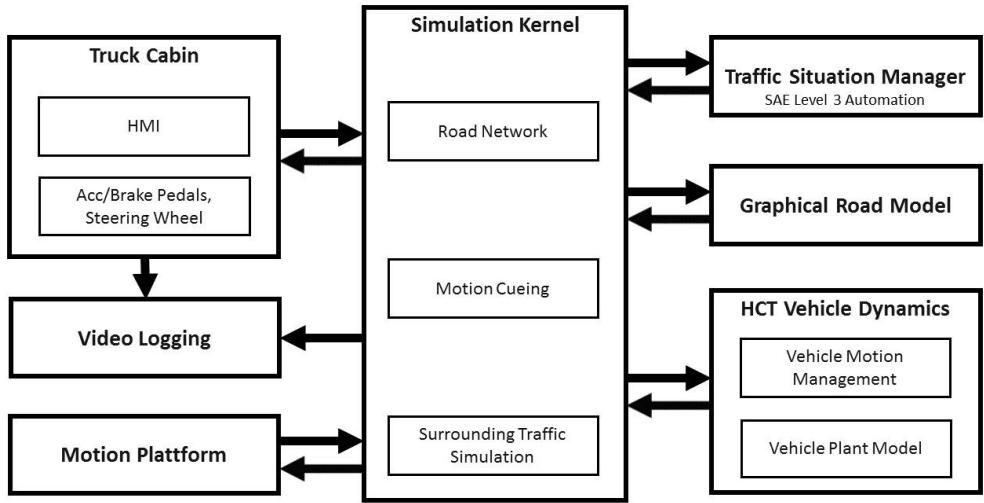
Figure 1: Overview of simulation layout.

Managing of vehicle motions was based on the layout presented in (Nilsson et al, 2015). From this, both traffic situation management and vehicle motion management functionalities carry over to the present study. In a nutshell the first function, figure 1 top right, formulates a strategy in terms of a desired path, taking in consideration road geometry, traffic as well as obstacles, whereas the second function, figure 1 bottom right, coordinates the vehicle actuators so as to enable the latter to follow the target path (Nilsson et al, 2015).

The vehicle dynamics module encompasses the vehicle plant model used to emulate truck motions, as well as the vehicle motion management unit.

The driver interface was located on the truck cabin which in turn was placed on the simulator dome. The truck cabin was that of a Volvo FH L2H1, figure 2, with little to no modifications. The conventional dashboard was removed and replaced with an LCD screen where a custom HMI was presented to the driver, containing information about truck states as well as feedback from the traffic situation management, figure 2.

Representation of the graphical road model was performed with 7 computers, each running an instance of the graphical engine VISIR, developed by VTI. These machines were on the receiving end of a constant stream of information from the simulation kernel, which contained positioning data concerning placement of all simulated vehicles. The graphical representation of the world was presented to the drivers using 9 projectors which displayed images on a curved screen, creating a window to the world with a field of view of about 180°.

Finally, the motion platform possesses 8 Degrees of Freedom (DOF) whose displacement references were generated by the motion cueing algorithm in the simulation kernel. These degrees of freedom are divided between a sledge, with 2 DOF in the lateral and longitudinal

Figure 2: On the left, truck cab mounted on SimIV. On the right, developed HMI including feedback of the traffic situation management functionality.

direction, on top of which is mounted and hexapod with the remaining 6 DOF, 3 rotations and 3 translational displacements. For more details on the hardware and its properties, refer to (Jansson et al, 2014).

4. Road Network

The simulated road was generated using a real multi-lane road as reference because it was possible to identify real world areas where lane-change accidents are more prone to occur, as pointed out in (Sandin 2015), but also due to the familiarity of the drivers with the driving stretch which further contributes to the feeling of immersion. Modelling of the road was performed under the ViP Knownroads project, (Nåbo et al, 2015). The latter focused on the development of real roads in simulated environments for the virtual testing of vehicles. A road network was developed which comprised of the stretches connecting the Swedish cities of Göteborg-Borås-Alingsås-Göteborg, as illustrated in figure 3.

These roads were selected due to their proximity to the test grounds Hällered and AstaZero, located in the vicinity of the star in figure 3, as well as due to the geographical proximity of Swedish automotive industry, which often uses this road network for testing (Nåbo et al, 2015). The road was modelled with the aid of real-world measurements from GPS and mapping information as well as local road properties in terms of banking, slope and shorter wave length data. A description of the road and its properties was stored using the Open*Drive* Format, (VIRES Simulationstechnologie GmbH, 2015). This description was used to generate a graphical model of the road network. Accurate height information on the surroundings and generic manmade structures were also added to the model. The presence of extra road features such as bridges, on/off ramps and road signs were added at a later stage. Figure 3 depicts the generated road model and its surroundings. For this case study, a specific multiple lane portion of the modelled road was selected from the network of the

city of Göteborg, Sweden. It comprised of a section of European road 6, from intersection Olskroksmotet to intersection Kallebäcksmotet.
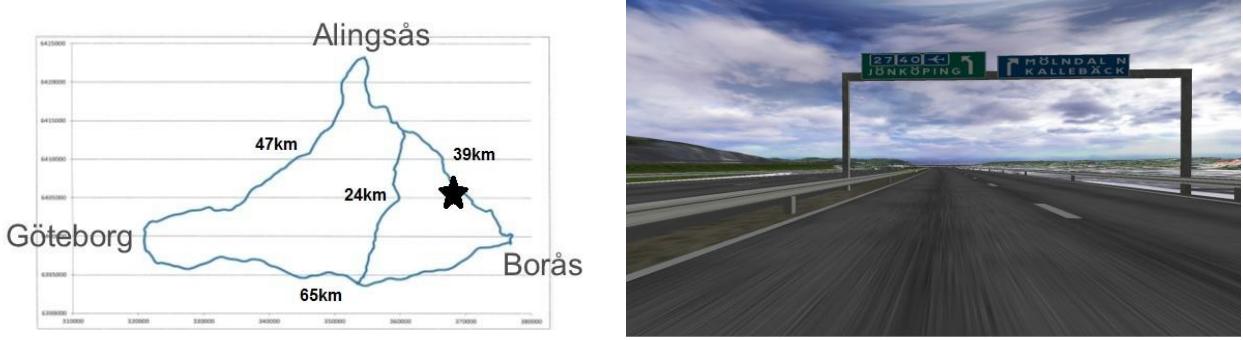
Figure 3: On the left, modelled road network and connected cities, courtesy of [5]. The star represents the approximate location of the Astazero and Hällered testing grounds. On the right, screen shot of the graphical road model in the vicinity of Kallebäcksmotet.

5. Vehicle Dynamics and Motion Cueing

Two different high fidelity truck dynamics models were used in this case study. Just as in (Sandin, Augusto et al, 2015), a tractor semi-trailer was selected to represent a standard heavy vehicle whereas a 32m A-double was chosen as a HCT. The A-double consisted of a tractor, semi-trailer, converter dolly and second semi-trailer, as introduced in Nilsson, P. and Sandin, J. (2014), with a total of 11 axles.

The vehicle models were designed as two-track models with the Virtual Transport Model (VTM) library. Chassis, cab suspensions, steering system, powertrain and brakes were all emulated all while also considering frame torsion flexibility and non-linear tire properties [6]. Extra degrees of freedom at the wheels were used to handle the road surface, passed on to the vehicle at each wheel as, height, roughness, banking and slope. Realistic modelling of off-tracking and reward amplification was one of the biggest focus points for the modelling tasks given their impact over control of lateral dynamics for heavy vehicle combinations. The quality and performance of the created vehicle dynamics models were validated against real-world measurements.

Not only the quality of the reproduced dynamics but also the performance of the vehicle dynamics simulation was regarded as an important criterion while modelling the vehicles. It is necessary to ensure that the models can be simulated at high enough frequency so as to represent all the dynamics of interest, while minimizing the load on the hardware.

Reproduction of the vehicle motions was achieved with actuation of the driving simulator motion platform. Each vehicle model had a virtual sensor placed in the cabin of the tractor, whose outputs, in terms of translational accelerations and rotation rates, were used as tracking signals for the motion cueing algorithm. The latter was a modified classical washout filter and was tuned with the

support of truck test drivers. Due to the characteristics of a lane-change manoeuvre, the tuning efforts were aimed at improving the recreation of lateral dynamics, i.e. lateral translational acceleration and roll rate, with little to no focus on longitudinal feedback.

6. Surrounding Traffic

Necessity for surrounding traffic arises from the need to immerse the driver in the driving task as well as to generate conditions of interest where the driver behaviour is to be studied, i.e. lane-change manoeuvres. For this experiment, surrounding traffic had three main design criteria: to block the lane head of the truck thus ensuring the latter always drives at the desired speed, to open and close a gap on the adjacent lane hence allowing a lane-change manoeuvre, and finally to adjust its speed according to predefined rules so as to provoke critical situations during lane-change manoeuvre conditions.

The surrounding vehicles were modelled as punctual dynamics since more detailed dynamics were deemed unnecessary for this experiment. Each vehicle could be individually regulated in two different modes, either speed or headway time control and were never allowed to change lanes. The vehicle controllers were selected according to the scenario demands and the control mode often changed in between both available conditions. Positioning of the traffic relatively to the truck changed as the experiment progressed, but the initial layout can be seen in figure 4.
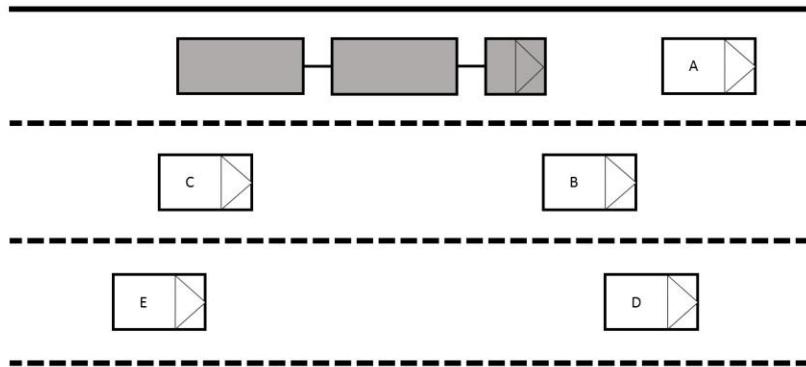

Figure 4: Layout for surrounding traffic at the beginning of the experiment. The truck controlled by the test subject is shown in grey background while the remaining vehicles are presented with a white background.

7. Traffic Situation Manager

For the presented case study, the driver support function focused on lane-change manoeuvres and fully automated driving. Considering the SAE standard J3016, (SAE J3016 Jan 2014.), this function

falls under conditional automation, automation level 3, see also figure 1. When active, the driver would no longer have to control the vehicle either with the accelerator/brake pedals or with the steering wheel and the truck would be driven autonomously in lane keeping mode. Longitudinal control was also performed automatically and would depend on the leading vehicle as well as road speed limits. The driver was responsible for the decision of changing lanes which was triggered by the turn indicator stick. Once the latter were activated, the truck would autonomously perform a lane-change manoeuvre taking in consideration surrounding traffic and road geometry. At all times, the driver was requested to be ready to take over from the system.

Under assessment were two types of functions which perform the task described above, a Driver Model Controller (DMC) and a Nonlinear Model Predictive Controller (NMPC). These solutions have previously been compared in Nilsson, Laine et al, (2015), where the vehicle dynamics performance as well as *satisficing* behaviour were evaluated in desktop simulations. The DMC performed longitudinal control based on (Lee,1976) and lateral control with a two-point visual model, (Salvucci and Gray, 2004), while traffic situation predictions were generated for each of the truck surrounding lanes in order to manage the automated driving task (Nilsson, Laine et al, 2015), For the NMPC case, longitudinal and lateral control actions were computed as solutions for a constrained optimal control problem. The latter describes the desired motion of the vehicle for a specific time horizon, taking in consideration surrounding traffic, lane keeping as well as comfortable driving (Nilsson, Laine et al 2015).

8. Driving Sessions and Events

Analysis of lane-change manoeuvres was the main goal set by this case study and it was achieved through manual and autonomous driving sessions in order to gather data on driver and driver assistance system performances. Collection of meaningful and comparable data implies that the driving environment and events, need to be designed so as to generate driving conditions that are in line with the specified goals. Drivers will behave in different manners making it important to account for the possibility of a wide variety of outcomes which are not always aligned with the experiment aims. This motivates a need for redundancy in experiment design, ensuring that the driver experiences similar situations more than once so as to map different types of possible reactions.

The simulator experiment was organized in 3 distinct driving sessions hereby referred to as A, B and C, figure 5. Driving session A, with a standard heavy vehicle, precedes session B, using HCT, both sessions driven manually. Session C, with HCT, came last and consisted of a mix of manual and autonomous driving.

Each of the individual sessions was divided into a set of independent runs. These consisted of training, a gap event, and two types of critical events, figure 5. Training was a short accustomization drive to the simulator which included braking tests and lane-change manoeuvres. The gap event was triggered by the turn indicator and forced the compact traffic in the adjacent right lane to open a gap thus allowing the truck to perform a lane-change manoeuvre. The critical events where much like the gap event up to the point where the lane-change manoeuvre was initiated. In Critical 1,

once the truck heading to the lane rises above a threshold, both vehicles ahead, in the current and adjacent lane, started braking. In critical 2, the vehicle ahead in the adjacent lane started to brake once the middle of the truck front axle crossed
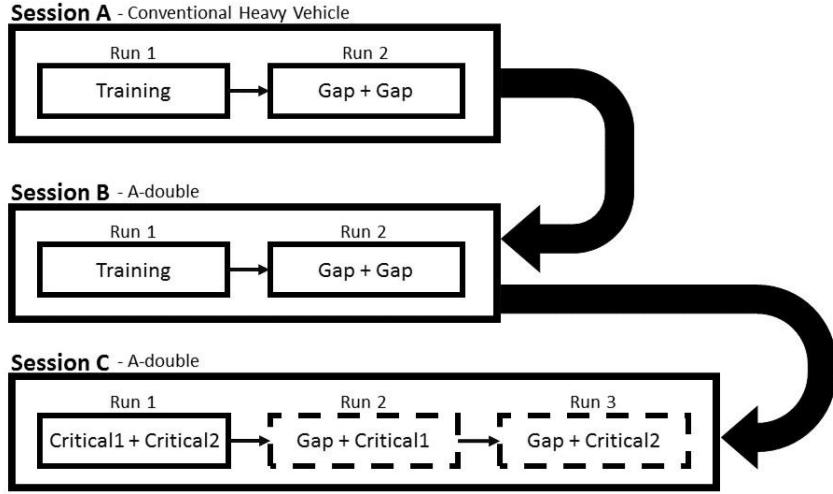

Figure 5: Depiction of experimental layout. Dashed runs implied autonomous driving while solid runs represent manual driving.

the lane markings. Whereas the gap scenario was set-up to investigate a normal lane-change manoeuvre, the critical events were designed to study simultaneous brake and steer actions by the driver.

9. Discussion and Results

The devised simulation architecture provided a solid base for integration of all components. No limiting bottlenecks were registered and information was shared in a reliable way. Integrating and testing of new vehicular systems, autonomous driving functionalities and driver assistance systems is a challenge due to their vast diversity and distinct features as well as interface possibilities. To handle these demanding conditions, simulator environments need to further improve flexibility in order to boost connectivity and streamline integration. This can be achieved by developing modular systems where all components of the simulation are well defined and possibly decoupled while using standardized interfaces to ease the integration of new applications, (Fischer, Richter et al, 2014). Major restructuring of existing simulator infrastructures could be a consequence of this solution and that might not be desirable. Taking for example the ADASIS V2 format (Ress, Balzer et al, 2008), where road map data is made available in a vehicular system, it could be desirable to instead specify a communication standard where the data of the simulated world is made available in a compact form. This would then allow any actors to reconstruct or directly access the required information on the surrounding world states independently of software and hardware platforms.

Designing a road network based on existing infrastructure proved to be added value to the experimental set-up. This is mainly due to the presence of real world features which could be

perceived by the drivers, in terms of banking and slope effects, for example. Also, to be able to integrate in the simulated world an environment which is linked to many of the real world problems under study, further consolidates and empowers the conclusions drawn from simulator driving sessions. This however comes with the cost associated with measuring and mapping all the road features. Depending on the desired level of detail and size of the road network under consideration, the development effort involves the interaction of different competence areas as well as resources to achieve the final result, which may not be time or economically feasible for the majority of cases. Further work needs to focus in identifying which road features are of interest for a simulation and how to port them from real world into the simulation environment with a minimal amount of effort.

Focus on the development of realistic, high fidelity vehicle models proved to be highly valuable for the designed case study. The vehicle model is the connection between the simulation and the driver so it is important that the latter receives feedback which can be correlated with real-world experience. This is tightly related to the motion cueing strategies which should be verified in a subjective manner by individuals with broad driving experience, in addition to more traditional objective tuning methods. The set-up put in place for this study received satisfactory approval levels from professional and test drivers, whose feedback was gathered subjectively after the simulator drives. Moreover, the fidelity of the vehicle dynamics also plays an important role on the study of the driver assistance systems since they are tightly coupled to vehicle handling. However, it is important to keep in mind that the development of such dynamic models is time and resource consuming. This implies that, if such tools have not been previously created, considerable effort will have to be allocated to their development thus placing a heavy burden on any experiment preparation.

The validity of the outcomes for the experiment conducted in this case study is tightly connected to the surrounding traffic. The latter is the tool used for the generation of driving conditions which ultimately influence the driver behaviour on the road, ideally leading to the type of meaningful situations the study aims at analysing. With the possibility for different control modes at the individual level, the traffic model used in this experiment proved to be satisfactory for the detailed and consistent behaviour required from surrounding vehicles. This however is not ideal for larger groups of vehicles given the big computational overhead introduced in the simulation, caused by the calculation and maintenance of all vehicle states as well as vehicles' relationship towards each other and the truck. Implementation of the algorithms which managed the traffic turned out to be a bulky task mostly due to the fact that they need to adapt to the driver behaviour in order to ensure comparable experiences for the different test subjects. Traffic simulation algorithms are available in great variety, however further effort should be placed unto designing versatile algorithms which are capable of adapting to the driver and autonomous driving systems, while still being controllable enough to establish circumstances outside the ordinary driving scope.

In this study, the vehicle sensors were not modelled according to real world references, either because they are non-existent or because they are too cumbersome to set-up at such early stage testing. Interface with the vehicle models and driver assistance systems was made in an unbounded way where all available environment and vehicle states exist with exceptional quality. This is regarded as an advantage while testing an idea or concept but possibly not optimal when using functionality which is closer to production. A simulator environment should have the possibility to

support both ends of the testing spectrum and further effort should be placed in modelling of real world sensors so as to better represent data collected during real-world driving conditions.

At such an early stage, the types of conceptual driver assistance systems hereby considered are rarely paired with HMI strategies. Since the driver perception of the system inner workings is of the utmost importance for function evaluation and acceptance, driver interface algorithms need to be available for these trials. It could be rather cumbersome to design dedicated HMI solutions at such an early stage, thus the possibility of using flexible HMI, with the capability to cover certain types of functionalities, should be considered for future applications.

10. Conclusions

The case study under focus was used to evaluate the feasibility of using large driving simulators for the design and test of future automated functionality for road transport. With this in mind, a test environment was developed with the goal to integrate HCV and autonomous safety functions in a large scale motion driving simulator. This implied the emulation of sensible vehicle behaviour, representation of realistic road networks, development of a conceptual autonomous driving functionality, traffic simulation and management of the interaction between all the former elements. The positive outcomes highlight the potential for driving simulators to be used in function development, testing and evaluation. As a malleable testing tool, the simulator mitigates the shortcomings of early function concepts by bridging the gaps between available and idealized technology or functionality. This means that usable data can be collected at a rather early stages thus contributing towards focused, more consistent and considerably faster development phases. It is important to understand that a driving simulator cannot replace real-world driving trials. Driving simulation should be seen as a complement to driving trials when considering this type of applications; a forgivable, safe and repeatable environment where there are almost no limitations in terms of applications and test conditions, used to reinforce ideas, gather early feedback/knowledge and further clarify real world testing needs.

As an initial study this work has provided insight over the suitability of driving simulators for the study and development of novel functionality in transportation as well as the study of new vehicle systems.

Much of the uncovered potential is documented as suggestions for future work, as described in section 9. Among the latter, special focus should be aimed at creation of a more general simulation architecture, improving of existing traffic simulation and modelling of real-world sensors to further connect simulators with real-world testing conditions.

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