Design and Performance of the VTI Sim IV

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Abstract – The VTI simulator IV (Sim IV) is the fourth advanced driving simulator designed and built at The Swedish National Road and Transport Research Institute (VTI). The simulator, taken into operation 2011, has an 8 degrees of freedom (DoF) moving base, a field of view (FoV) of 180 degrees and features a system for rapid cabin exchange. With a budget of roughly 2,4 M euro; Sim IV was developed to provide VTI's newly established Gothenburg office with advanced driving simulation capability, and to be a cost efficient complement to the Sim II and Sim III facilities in VTI's Linköping office. This paper describes the design and technical performance of the facility. A brief summary of results and experience from validation studies for the first three years of operation is also presented.

Key words: Driving simulator, Simulator design, VTI, 8 DoF, Simulator performance.

1. Introduction

VTI is a governmental research institute organized directly under the Swedish Ministry of Enterprise, Energy and Communications. The research deals with issues concerning the transport system, and much focus is given to road transports. One major area of attention is the individual's behaviour in the transport system. To study human factor issues driving simulators have been an important instrument, at VTI, since the 1970:ies. VTI's first moving base simulator was the Sim I [Nil1,Nor1]. Officially taken into operation in 1984, the Sim I was the first moving base simulator using a long linear track to produce large stroke lateral displacement of the cabin. In 1994 the Sim II [Jer1] was introduced. Sim II has a similar physical layout as Sim I, the only major difference being that it was designed for a truck cabin. In 2004 Sim I was replaced with Sim III, [Nor2]. With a linear drive system achieving close to 1 g Sim III added improvements to the sheer acceleration performance of VTI's simulation capabilities. The fact that Sim III's linear system can be used in either the longitudinal or the lateral driving direction was also a novelty for the VTI simulators. Sim I-III have very similar overall design i.e. a 3 or 4 DoF moving base (linear track, pitch, roll, yaw(only on Sim III)) complemented by a 4 DoF shaker table (0,1 m actuator displacement) to provide the high frequent (up to 10 Hz) simulation of road roughness, i.e. movements relative to the projection screen. This design together with a 120 degree FoV provides good simulation capability especially for highway and rural road driving scenarios. The VTI Sim IV, in Figure 1, was designed to complement Sim II and III.

Figure 1. The VTI Sim IV

In particular it adds a wider FoV (see Figure 2) and more degrees of freedom in the moving base. The Sim IV is equipped with one hexapod with six degrees of freedom (roll, pitch, yaw, surge, sway and heave) which in turn is mounted on a sled with two extra degrees of freedom (two orthogonal directions for translation, longitudinal and lateral).

Figure 2. Interior platform view of the Sim IV

Together, they make Sim IV capable of dealing with lesser curve radiuses and give a more realistic sensation of stop and go traffic. This type of conditions is typically found in urban area scenarios, thus Sim IV is in many cases the simulator of choice for city driving studies at VTI.

Discussions on building a Simulator in Göteborg started in 2007 at the same time as the start-up of ViP was being planned In the spring of 2008 a pre-study [Jan1] was conducted to investigate the possibility to build a VTI facility in Göteborg, and a decision to start up the building project was taken in the late fall of 2008. After some delays and changed plans the facility was inaugurated by the Swedish minister of infrastructure on the 18:th of May 2011. The decision to establish a new driving simulator at VTI was motivated mainly by the start-up of a new competence network on driving simulation ViP – virtual prototyping and assessment by driving simulation [Vip1]. Sim IV provides advanced driving simulation capability to VTI's newly established Göteborg office as well as to the west-cost partners of the ViP consortium. Similar to the Sim II and III the Sim IV is used to provide human factors researchers with realistic driving situations that can be completely controlled and repeated. However, applications where the simulator is used as an advanced systems integration platform and a tool for complete vehicle testing in vehicle development has gained increasing attention.

The design of the Sim IV facility was influenced by several factors. Cost effectiveness and constraints to the budget is always one of the major factors. For Sim IV this meant that reuse of simulator technology from Sim II and III was an important issue. Another hard constrain was the available office building, which creates hard limitations on the size and proportions of the simulator.

2. Simulator performance and specifications

This section describes the technical specifications and data of the facility. The design of any advanced driving simulator is influenced by several different factors. The most important high level requirements on the design of Sim IV are given in Table 1, below.

Table 1. High level requirements on the Sim IV facility

The facility should be a high fidelity simulator e.g. providing a high fidelity simulation of all impressions of real driving including motion feedback.
It should be possible to simulate both heavy and light vehicles, requiring the possibility to change cabin rapidly.
The operational area of the facility is 12 x 15 x 7 (length x width x height).
The Budget for the project including hardware, person hours and consultants was 23,26 MSek (equivalent to 2,44 M euro, by 2014-05-21 exchange rate).

From the top level requirements in Table 1, a first design was conceived and refined to the final solution that was eventually installed. Many of the most challenging design issues came from keeping the platform within the weight and mass moment of inertia limitations of the moving base system. Also, the fact that a complete truck cabin should be mounted complicated the design of the visual system. Much effort went into finding a design of the visual system. The challenge was to achieve a front projected forward image where the roof of the truck cabin did not obscured the beam of the projector. A second issue worthy of much attention, was the structural rigidity of the platform. To ensure high enough eigen frequencies of the entire structure the cabins are used as a stabilising part of the platform increasing its rigidity (this can be seen in Figure 3 where the beams connecting to the rear back corners of the cabin are visible).

Figure 3. This picture show the beam connecting the back corner of the cabin to the platform structure.

2.1. Moving base

The moving base/motion system, in Figure 4, provides the driver with motion feedback by moving the platform that the cabin is mounted on. A motion cueing algorithm [Fis1] is used to transform the motion of the simulated vehicle into a reference motion for the moving base. In Sim IV the moving base consist of a linear sled system that can provide large stroke linear motion in two directions (the vehicles longitudinal and lateral direction). On top of the linear drive system a hexapod/Stewart motion platform [Ste1] is mounted.

Figure 4. The moving base of Sim IV consist of a bi directional large stroke linear system and a hexapod. In this case a commercial solution that has been deployed in several other advanced driving simulators.

This system can generate displacements in all three translational DoF as well as the three rotational DoF. The entire moving base is therefore said to have 8 DoF, indicating that the actuator space has 8 DoF. The motion cueing that is used in Sim IV is further described in [Fis3]. The maximum payload is 2500 kg. In Table 2 and 3 some of the basic performance specifications of the moving base is presented.

Table 2. Hexapod performance

	Excursions	Vel.	Acc.
Surge	-408/+307 mm	±0.80 m/s	±6.5 m/s^2
Sway	-318/+318 mm	±0.80 m/s	±6.0 m/s2
Heave	-261/+240 mm	±0.60 m/s	±6.0 m/s2
Roll	-16.5/+16.5 deg.	±40 deg./s	±300 deg./s2
Pitch	-15.5/+16.0 deg.	±40 deg./s	±300 deg./s2
Yaw	-20.5/+20.5 deg.	±50 deg./s	±300 deg./s2

Table 3. Sled system performance

	Excursions	Vel.	Acc.
Surge	+/- 2.5 m	+/- 2 m/s	+/- 5 m/s2
Sway	+/- 2.3 m	+/- 3 m/s	+/- 5 m/s2

2.2. Visual system

The visual system consist of a forward screen and two, or more, lcd displays. The lcd displays are used as rear-view mirrors and the number depends on which cabin is used. The forward screen (see Figure 5) uses front projection technique and currently 9 projectors, with a resolution of 1280x800 pixels, projects the image on a curved screen with a diameter that varies between 1.8 (to the left) and 3.1 m (to the right) and a height of 2.5 m. The field of view is approximately 180×50 degrees.

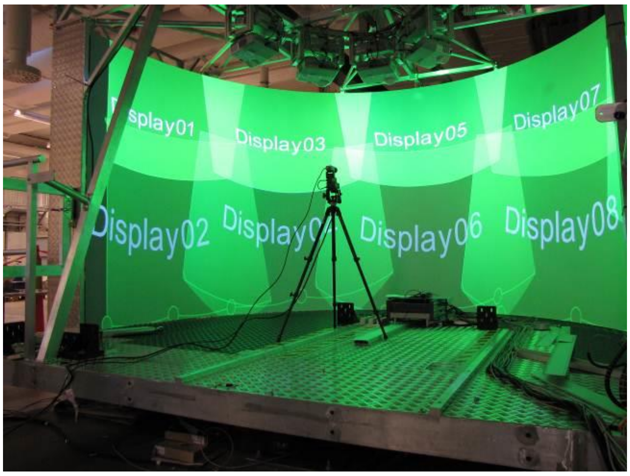

Figure 5. A test setup of the front projected forward view here eight projectors are used to cover the screen.

The forward FoV varies slightly, depending on cabin (the nominal position of the drivers head varies slightly between truck and passenger car cabin). Table 4 describe the important characteristics of the visual system.

One of the major challenges with the visual system was to provide a unobscured FoV to the driver position. During the project different display solutions where discussed. The final design was to use a front projection solution. Because of the overall constraints on the simulators height and the mass moments of inertia, the projection screen is closer to the cabin than in Sim II and III. To avoid the truck cabin from obscuring the path of the projector beam, projectors with a very short throw distance were required. The combination of a short throw distance and curved screens require a significant effort for warping and merging the projector images. In the Sim IV a dedicated commercial system is used for this purpose.

Table 4. Visual system specifications

FoV	180×50 degrees
Average resolution on screen* (arc minute per line pair)	5,0** (horizontal) 2,5** (vertical)

*The human eye has 0.59 arc minute per line pair

** ± 0,5

2.3. Sound system

The sound system consists of a 6.1 surround system; two speakers at the front, two at the sides and two behind the head plus a subwoofer. These speakers are controlled by a separate computer which can play sound in any of the speakers. The Sim IV was the first facility where directional sound from objects outside of the cabin was used. The added value of directional sound has not been thoroughly analysed, but the subjective rating of every one who tried both configurations is that that the directional sounds adds a significant sensation of immersion in the simulation.

2.4. Simulator software

Reusing technical solutions and simulation software was one of the most important measures to keep the overall cost of the Sim IV down. The simulation software, is to a very large extent based on own development and open standards. It was already in use in the Sim II and III facilities. The software can be divided in three main components.

1. ViP Core – the main software to run the simulation, contains scenario, vehicle dynamics and several other components. The main simulation loop executes at 50 Hz.
2. VISIR – renders the computer graphics and also contains some script tools to generate roads. The logic description of the road is according to OpenDrive. Graphics rendering executes at 60 HZ.
3. SIREN – Is the software to produce sound [And1]. It is based on OpenAL and can assign a direction to any sound and play both recorded sounds (e.g. in vehicle warnings) and sounds from a sound model (e.g. for the wind, engine and tire noise and sounds from other vehicles).

The software is shared and co-developed within the ViP competence network and anyone interested in using it can apply for membership.

2.5. Cabin exchange

An early design requirement was that it should be possible to simulate both truck and passenger car driving. The facility is currently equipped with two cabins one Volvo XC 60 (small SUV passenger car) and one Volvo FH16 (truck cabin). To exchange cabin the moving base is placed in a settled position in the rear part of the simulator hall. A table is attached to the rear part of the platform. The cabin is then slid out on the table on a rail (visible in Figure 6). The cabin is lifted down from and up onto the table by a permanently installed crane, installed just outside of the simulator hall.

Figure 6. A permanently installed crane is used to lift cabins onto the platform.

If the procedure is well planned and all software interfaces are tested a cabin switch can be accomplished in less than a day.

2.6. Costs

The project had an overall budget of 23,259 MSek (2,44 Meuro). The budget covered costs for hardware, consultants and the person time for the VTI personnel, also including project management tasks. The main project was split in 8 sub-projects: moving base, platform, visual system, computer system, truck cabin, passenger cabin, sound system and integration. The single most costly subproject was the moving base project which had a total cost of roughly 1 M euros.

Table 5. The costs for building Sim IV, actual costs.

Costs	[MSek] / [Meuro]
Hardware and consultants	10,837 / 1,140
Person time (only VTI personnel)	12,337 / 1,298
Total costs	23,174 / 2,438

The final cost of the project ended up very close to the budget with a difference of roughly 10 Keuro lesser costs than planned. However, some major maintenance/upgrades where done rather quickly after the inauguration and these are not included in the budget. The most notable work was the moving of the attachment point of the platform to the hexapod. The centre of mass of the whole structure was miscalculated by 15 cm in the longitudinal direction. This required more than 100 kg of counter balances to be added for the first months of operation. After that continued tuning, smaller repairs, upgrades and improvements has been carried out as part of the normal maintenance.

3. Studies and initial experiences

Since taken into operation (spring 2011) and until the spring of 2014, 14 scientific simulator studies has been carried out in Sim IV (omitting studies carried out in master thesis works and demonstration activities). Many of these projects are still ongoing and have yet to disseminate the results. Below some of the projects are briefly described.

3.1. Lane departure scenarios used for the evaluation of active steering interventions

[Fis2] describe the development of a lane departure scenario that has been used successfully in Sim IV to evaluate the efficiency of active steering-wheel interventions. The lane departure scenario is designed in such way that the vehicle at a given position is moved across the median towards an oncoming vehicle, or towards the left road edge. This is accomplished by introducing a steering angle in the simulated vehicle without presenting the corresponding lateral acceleration with the motion system. This is done in parallel with a visual task that occupies the driver, so that s/he will not notice anything out of the ordinary until s/he looks up. The visual task consists of reading numbers from a screen placed at a relative large down angle (40-45 degrees). Each number is displayed for 0.3 seconds, with 0.2 seconds of blank screen in between numbers, creating the total task duration of 2.8 s.

In order to execute the described scenario and thus to trigger the active safety system correctly, a lot of requirements have to be fulfilled. The signals from lane and radar sensors have to contain correct, realistic information about the virtual environment, drivers have to be successfully distracted and finally the visual, acoustic, haptic and vestibular feedbacks have to closely resemble the real experience in order to trigger realistic driver reactions to the system intervention. That means that all involved feedback systems (i.e. graphics, sound system, force feedback steering-wheel and the motion system) need to have appropriate performance characteristics.

The lane departure scenarios have successfully been used to evaluate up to almost 100 drivers' responses to active steering-wheel interventions intended to prevent cars to enter the opposite lane or to cross the left road edge. The drivers' responses have also been validated towards drivers' responses of unexpected steering-wheel interventions in a real vehicle on a test track. These drivers were given the same visual task, and got the interventions while driving straight.

3.2. Simulator experiments for the development of quantitative driver models in the evaluation of active safety systems

Behavioural data have been collected by means of specifically designed experiments in order to develop and verify quantitative models of driver behaviour. Behavioural data have also been collected from ongoing Field Operational Test (FOT) projects for the verification of driver behaviour and experiment scenario. The quantitative models are intended to be applied within industry, research institutes and academia in computer simulations with the purpose of evaluating, verifying and/or tuning active safety systems.

Identified main areas of needed new model development include driver inattention and expectancy, driver reactions to active safety control interventions, and nuisance warnings/interventions. The active safety systems that have been implemented and evaluated in the simulator experiments are active steering-wheel interventions (mentioned above) in passenger cars and an Advanced Emergency Braking System (AEBS) for heavy vehicles. The experiments in Sim IV have been very successful and the final data analysis is underway. Several publications are expected in the near future. The research has been conducted in close collaboration between VTI, Swedish vehicle OEMs and Chalmers University of Technology.

3.3. Evaluation of methods for measuring speed perception in a driving simulator

A project including experiments and literature review on speed perception in a driving simulator was conducted in the Sim IV. Result from the study shows that the ability to estimate speed differences correctly depends on the base speed, more results are presented in [Fis2].

3.4. High speed control

Validation of the vehicle dynamics of a 32 m heavy vehicle combination (an A-double). The topography and roughness of a real country road have been modelled in the simulator environment. Experienced truck drivers have driven the 32 m vehicle on the modelled country road.

3.5. Known roads

The Known roads focus on creating highly realistic road descriptions from different available data sources. The project uses the OpenCRG format to described road topology. New methods for generating the road side visual appearance from national geo data is also included in the work. The goal of the project is to make the roads connecting Gothenburg, Borås and Alingsås. The project has particular focus on HGV handling and the possibility to compare simulator driving with on road driving for handling purposes. The project has a close connection to the one described in section 3.4.

3.6. Sleep Noise

In the Sleep noise experiment [For1] road noise models where constructed and validated with road noise measured from a real vehicle. Two vehicles where measured and modelled. The models where then used in experiments with alert and sleep deprived drivers to study the effect of normal and high road noise and the effect of driving in an older vs. newer, more quite, vehicle.

4. Summary

This paper describes the VTI Sim IV. An advanced driving simulator with 8 DoF moving base. The facility has proven to be a valuable tool for human factors research. After 3 years of operation 14 studies have been run. The studies are a mix of HGV and passenger car experiments and switching between cabins works well. The facility complements the other VTI simulators in that it provides a wider FOV and more DoF to the moving base (in particular large stroke linear motion both laterally and longitudinally). Most of the simulator software was reused when establishing the Sim IV. The main development of VTI's simulator technology, connected to the Sim IV establishment, was the sound software and to some extent the motion cueing. Continued development and improvement of the facility is constantly on going to meet the need of new research projects.

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