SHAKE – an approach for realistic simulation of rough roads in a moving base driving simulator

Anne Bolling, Jonas Jansson, Anders Genell, Mattias Hjort, Mats Lidström, Staffan Nordmark, Göran Palmqvist, Håkan Sehammar, Leif Sjögren, Mikael Ögren

Swedish Road and Transport Research Institute
S581 95 Linköping, Sweden

anne.bolling@vti.se, jonas.jansson@vti.se, anders.genell@vti.se, mattias.hjort@vti.se, mats.lidström@vti.se, staffan.nordmark@vti.se, göran.palmqvist@vti.se, hakan.sehammar@vti.se, leif.sjögren@vti.se, mikael.ogren@vti.se

Abstract – *With today's advanced measurement equipment for measuring roads, it is possible to measure road geometry at high precision within a large span of wavelengths. Detailed information about the roads longitudinal and lateral profile, including macro texture, would in theory be sufficient for a realistic reproduction of road induced vibration and noise in a driving simulator. Especially, it would be possible to create a direct connection between the visual information of the road condition and the ride experience, which would increase the level of realism in the simulation. VTI has during three years performed an internal project called SHAKE with the aim to develop and implement models in VTI driving simulator III that use measured road data for generating realistic vibrations and audible road noise connected to the visual impression presented on the projection screen. This has indeed resulted in an more realistic driving experience, and a validation study with test persons driving both in the simulator and in the field has been undertaken. The OpenDRIVE standard is used as a framework for describing the road properties (e.g. visual, vibrations and noise). For this purpose some augumentations to the OpenDRIVE standard had to be made. This paper describes the technical implementations in the driving simulator, along with results from test drives on the implemented road sections*

Introduction

High-fidelity simulation is about creating an as true to life driving experience as possible. To accomplish this several components, such as e.g. visual impression, audible sensation, motion sensation, are required. In each of these fields much work has been done and is still on-going, e.g. (Kawamura, 2004). To achieve a realistic experience it is also important to synchronise these sensations i.e. the visual impression should be connected to what is felt and heard by the driver. The problems associated with the lack of road irregularities is disscused in (Green, 2005). The purpose of this project has been to achieve better realism of the road surface and to understand how different road surfaces is perceived by the driver.

Simulator

This work was carried out in VTI's driving simulator 3 (Figure 1). This simulator is particularly well suited for this development due to its unique dedicated vibration table, which is capable of reproducing high frequent road vibrations. Furthermore, it is equipped with a passenger car cabin and an advanced motion system for realistic simulation of forces felt when driving (Nordmark *et al*., 2004; VTI, 2010-03-26). The surroundings of the driver are shown on a main screen with 120 degrees field of view, as well as in three rear view mirrors. The dedicated vibration table, which simulates road irregularities, is situated under the cabin and provides vibration movement relative to the projection screen. The motion system also provides high performance linear lateral acceleration, as well as roll and pitch movements of the entire platform.

Figure 1. VTI Simulator III

Vibrations

Driving simulator tests, to study road user behaviour, can be improved by creating a driving experience as close to real life driving as possible. One part of this is to include effects and behaviour that is introduced from a realistic road representation including the road's condition such as ruts, cracks, irregularities etc. Therefore a first test was done to accomplish this. Three sections on real roads were selected. The sections were 3-4000 meter long. They where chosen to cover a spectra of different evenness, one was judge as smooth (IRI = 1.1 mm/m), another as rough (1.7 mm/m) and the third as very rough (3.5 mm/m). The vibrations induced by the unevenness were measured with a personal car, Audi A6 Avant 2006. Accelerometers (3 axes) were mounted in the car chassis, on the driver seat and on the steering wheel. The Audi was driven several times in different speeds over the sections. During the runs data was collected. At least three participants gave, after repeated test runs, their opinion on the sections unevenness performance. During the development the same persons was used to subjectively rate the reconstruction in the driving simulator. The geometry and road surface condition was also measured with a dedicated road surface tester system. VTI has at its disposal a special measurement system, VTI Laser RST, (see Figure 2) designed and built to do high precision monitoring of the road surface condition.

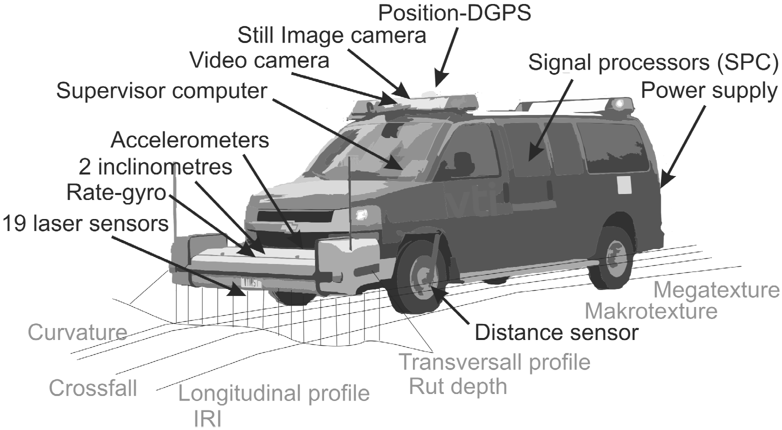

Figure 2. VTI Laser RST

The VTI Laser RST consists of a data collection system and sensors mounted on a van. The system can measure the road condition in traffic speed (speed independent).

Road condition is defined as a number of measurable indicators; see Figure 3 representing the relevant road surface characteristics, such as transversal unevenness expressed as rut depth, longitudinal unevenness expressed as IRI (International Roughness Index) and the surface texture expressed as MPD (Mean Profile Index).

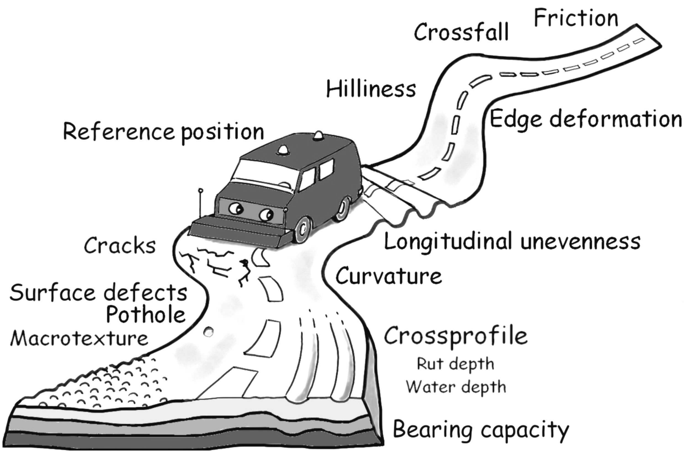

Figure 3. Road surface characteristics

Vibrations from a real road have previously been used in various studies in VTI´s driving simulators. The vibrations were generated by modelling each tyre as a vertical spring/mass/damper system, excited by a point following the road envelope. Traditionally, however, the road data input has been in the form of FFT transformed road data, and a longitudinal profile with the same spectral distribution as the measured road had to be created. The resulting longitudinal profile consisted of only one wheel track, leading to vibrations that were purely vertical without any roll or lateral movement.

This vibration model has since then been improved considerably, resulting in a major enhancement in simulation realism. The new vibration model is based on measured road profiles in both wheel tracks. The most important improvements are:

- A new model for representing the wheels has been developed, where a lateral stiffness component of the wheel has been introduced, together with a relaxation length model. This lateral stiffness affects the vertical position of the roll axle, and is needed for realistic roll and lateral movements.
- The movements of the simulator have been optimized with respect to both outer and inner movements of the system.
- Different locations for the center of roatation, of vibrations induced in the vehicles roll behaviour, has been investigated. This research is still ongoing.

The vibration model uses a time step of 0.5 ms for the calculations, while the simulator movements are updated with a frequency of 200 Hz.

The vibration model was developed, and validated by using the following procedure:

1. A passenger car was equipped with accelerometers and rotation sensors, and the vibrations from driving on a few different roads with a roughness varying from smooth to very bumpy were recorded.
2. The recorded vibrations were sent as input signals to the driving simulator movement system, to verify that the simulator was capable of reproducing the vibrations.
3. The road sections used for the vibrations measurements were measured with VTI´s sophisticated Road Surface Tester, which measured the road profile with high precision using several laser beams.
4. The new tyre model was developed, and with the measured road geometry as input, vibrations was generated and measured in the driving simulator. These vibrations compared well with those measured on the road.

Simulated road noise

The most important contributor to the interior sound environment in a car cabin is the tire/road noise. It dominates the interior sound for normal driving speed ranging between 30 - 120 kph. The mechanisms involved in noise generation are very complex and a real time application of a detailed noise generation model that creates realistic noise and vibrations is a futile approach due to computation cost. In the VTI Simulator III the approach is instead to create a realistic experience for the driver by relatively simple means based on standard road surface roughness measurements available to VTI. The model involves a number of simplifications, and comprises only three main parts: a velocity dependant noise generator, a static global transfer function and a sound effects generator. The noise generator very simply mimics the spectrum variation of the noise due to speed variations by applying an adaptive low-pass filter to a white noise signal. The static transfer function is estimated from road texture data and in-car noise measurements. The sound effects generator creates events such as driving through a pool of water, by filtering and randomly phase-shifting high frequent noise, or driving over a crack in the road, by creating a highly damped sinusoid similar to that from tire cavity resonance or suspension resonance. Modelled and measured road noise levels show reasonably good similarity, and informal listening confirms the adequacy of the simulated road noise.

OpenDRIVE – Patch augumentation

Since the vehicle position on the road surface or lateral distances relative to road or lane borders are important measures for the new vibration model, a comprehensive definition of the road has been necessary.

Traditionally, most simulator environments have used their own proprietary formats for the logic description of the road system, which has made it impossible to share road data between simulators. In 2006, an initiative to create an open format for the road description was initiated by the Vires company. The format “OpenDRIVE” (OpenDRIVE, 2010) has since then been accepted by several simulators and may become part of a future standard of road description.

VTI has used the OpenDRIVE format since 2007 which has improved the definition of the road and road surface significantly, which greatly facilitated the realization of the SHAKE project. A detailed description of the OpenDRIVE file format can be found at opendrive.org.

OpenDRIVE is a means for separating a road network into a set of roads, connected by junction areas or directly linked to each other.

A road is described by its geometry, lanes and objects.

The road surface is defined as a material name. VTI has added extensions where the material name is translated to visual appearance, audio and vibration data that describes the surface, see Figure 4. The OpenDRIVE specification of the road surface material indicates what material is used on each specific lane of the road from a start position.

Unfortunately there was no way within OpenDRIVE to specify patches on the road surface – areas where the surface was defect or repaired with a different surface material. The existing object description method was not detailed enough why we had to define a patch method. This defines a minor area, within a lane, where a different surface material is used (see Figure 5). This extension was later included in OpenDRIVE 1.3.

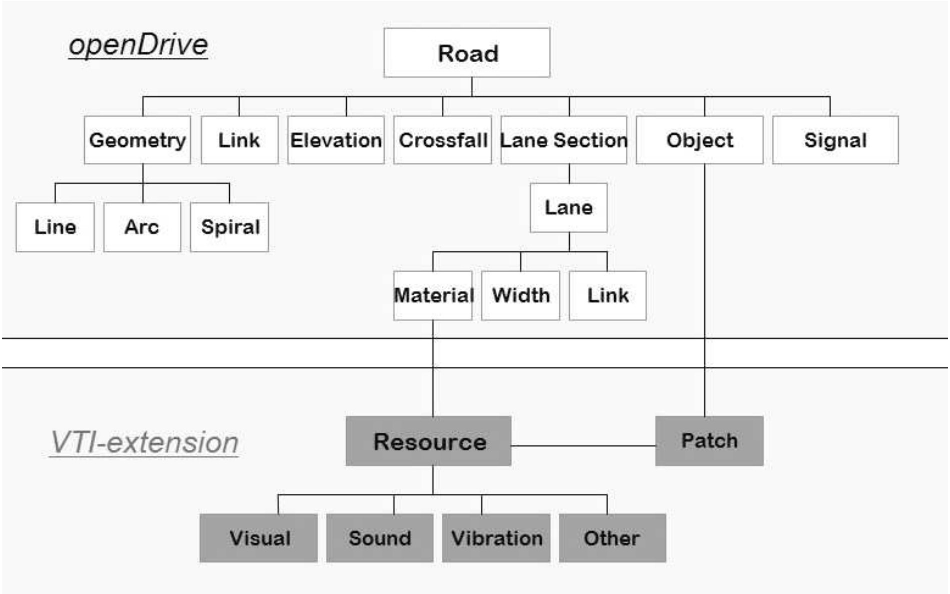

Figure 4. OpenDRIVE and VTI's extension

Figure 5. Example of a road with cracks and patches

Evaluation of road realism

During the development several comparisons between real driving and simulator driving where performed. In a larger experiment 32 test participants evaluated eight road surfaces conditions/properties as follows: Patched road, Road with ruts, Ruts with water, Road with rough texture, red, Uneven road 1- medium vibrations (ruts, patches, cracks, edge deformations), Road with cracks in the right wheel track, Road with cracks in the right wheel track and edge deformations, Uneven road 2- greater vibrations (ruts, patches, cracks, edge deformations), Each participant graded the realism of each roadsection between 1 and 7, where 1 is very unrealistic and 7 very realistic.

Table 1. Perceived realism of the different roads, the number of test participans is 32 for each road

	Mini-mum	Maxi-mum	Mean	Std. Deviation
Reference road	3.00	7.00	6.0313	.96668
Patched road	2.00	7.00	5.8438	1.11034
Road with ruts	1.00	7.00	5.2188	1.26324
Ruts with water	2.00	7.00	5.8437	1.22104
Road with rough texture, red	2.00	7.00	5.7500	1.21814
Uneven road (medium and heavy) vibrations (ruts, patches, cracks, edge deformations)	5.00	7.00	5.9375	.71561
Road with cracks in the right wheel track	3.00	7.00	5.7500	1.04727
Road with cracks in the right wheel track and edge deformations	4.00	7.00	5.6875	.96512

Overall all roads were judged to be realistic and received high mean values (between 5.2 and 6.0, where 1 represent a very unrealistic impression and 7 a very realistic impression). Figure 6 shows examples from the different roads.

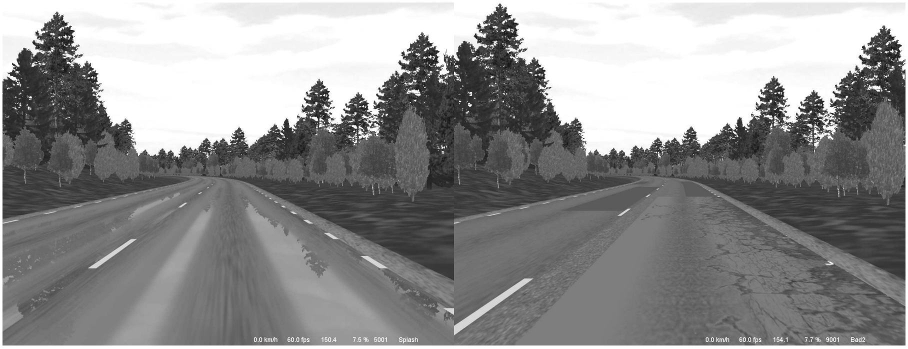

Figure 6. Example of two of the roads (ruts with water and road with cracks in the right wheel track and edge deformations)

Results

This study focuse on the realism of the simulated road surfaces. The development resulted in a augumented version of the OpenDRIVE standard, that facilitated a unified way of describing the roads properties. This description includes how the road appears visually to the driver , the tire to road noise heard by the driver and vibration sensation felt by driver. The proposed extension of a road patch definition was later included in OpenDRIVE 1.3.

The vibration models that where used as well as the tire to road noise model was validated using on road measurements, both using accelerometer measurements and subjective evaluations. These models where then used to implement 8 different roads/surfaces, which where used in a study to evaluate the drivers opinion on road maintenance quality (Ihs *et al*.,2010).

The general result from 32 test participants was that all roads where perceived as realistic. All roads received high mean values (between 5.2 and 6.0) on scale ranging from 1-7, where 1 is very unrealistic and 7 very realistic. The highest score was assigned to a reference road, that was designed to represent an average road with a normal amount of irregularities and patches.

Discussion and conclusions

The OpenDRIVE standard was used to specify all properties (i.e. visible, vibrations and audible) of a road surface in a logical road description. This forms the basis for the feed-back generation in the driving simulator. The tire position on road surface activates sound and vibration for each wheel according to road and patch definitions in the OpenDRIVE database. To facilitate this, an extension to the current standard was made. The extension consists of assigning a particular road surface appearance, vibration model and noise model to the description of lane material. Furthermore, the concept of a patch that represents a defined subset of the lane area is also introduced.

Because of its capabilities to reproduce cabin vibrations in the ride comfort range, VTI's Simulator 3 proved to be extremely useful to simulate road irregularities and unevenness.

The introduction of standardized road description provides a good foundation for a unified description of the road network and the road surface properties. The syncronisation of visual, audible and haptic impressions is important to create an overall realistic simulation experience in the simulator. Evaluation of the importance of the roll centre of roation for the induced vibrations is still on-going.

Keyword: OpenDrive, road, vibrations, roadnoise shake

Bibliographie

Nordmark, S., Jansson, H., Palmkvist, G., Sehammer, H., (2004) The new VTI Driving Simulator – Multi Purpose Moving Base with High Performance Linear Motion. *In Proceedings of the Driving Simulator Conference 2004 Paris, 45-55.*

Green, P (2005); How Driving Simulator Data Quality Can Be Improved; In Proceedings of the Driving Simulator Conference 2005 North America, Orlando, USA, November 2005.

VTI (2010-03-26). *VTI's drivning simulators*. Internet 13:09 2010-03-26 http://www.vti.se/simulator

OpenDRIVE. Internet 11:39 2010-05-07 http://www.opendrive.org

Ihs, A., Andersson, J., Kircher, K., Bolling, A.,(2010); *Trafikanternas krav på vägars tillstånd – en körsimulatorstudie (Road users´ requirements on road surface condition – A driving simulator study)*. Swedish National Road and Traffic Institute. VTI rapport 669.

Kawamura,A., Shirakawa,T. and Maeda,C. (2004*); Applicability of Driving Simulator as a New Tool for the Pavement Surface Evaluation,* Proceedings of the SIIV (Italian Society for Transportation Infrastructures) 2004 International Congress, Firenze, Italy, 52-10