Driving simulators, trends and experiences

Staffan Nordmark

Introduction

Driving simulators have been around for a number of years now. Compared to the flight simulators the limited number of advanced driving simulators is notable even in a global perspective. Economical reasons govern this. Very expensive real vehicles for which the operation involves risky manoeuvres justify the use of an expensive simulator for training purposes at a high cost per hour. These arguments are valid for airline and jet fighter pilots as well as tank and submarine crews. However for passenger car and truck drivers such a favourable cost-benefit ratio does not exist. Thus one may only expect to find advanced driving simulators at research institutes or automotive manufacturers where research or development may justify the high costs. Driving simulators have also proved to pose some new severe technical demands not normally encountered in flight simulators. To some extent this has also created new challenges for the simulator industry. It is typical that all the advanced driving simulators built to date do not look the same at all. This is in sharp contrast to flight simulators where the standard hexapod is completely dominating. It is very confusing to the layman that a simulator for an ordinary passenger car should be more complex and in some aspects technically more advanced than that for a jet fighter or a jumbo jet. The car driver can perform very quick manoeuvres with accelerations changing in both direction and amplitude when driving slalom between cones or avoiding an obstacle by turning the steering wheel very fast. The road and interacting objects like other cars, signs, etc. show up at a fairly close range to the driver. The importance of short time delays in driving simulators may then be intuitively grasped when comparing the view of a driver to that of a pilot where the landscape is several hundred meters away. This results in the need for

- moving bases with large linear motion
- visual systems with extremely short time delays
The evolution of driving simulators during the later years has thus followed two lines. Everyone seems to agree that a moving base will add to the realism but the cost factor has deterred people from building such systems. A multitude of fixed base simulators have appeared during the last years ranging from modified arcade games to scaled down custom built simulators. The full range driving simulators with large moving bases are comparatively rare but a number of them has appeared predominantly in Europe but also in Japan. This presentation will mainly confine itself to driving simulators with moving bases but the observations and comments on the visual systems are of course applicable to fixed base simulators as well.

**Historic development**

VW (Volkswagen AG) built the first driving simulator with a more elaborate moving base (Figure 1a) in the beginning of the seventies [1]. This system relied entirely upon tilting the cab in different directions using a component of the gravitational force for simulating linear accelerations in the plane. The 3 DOF (degrees of freedom) moving base comprises roll, pitch and yaw. Added to this some vibrations could be introduced in the driver's seat to enhance the road feeling. The cab is just a driver's seat with a steering wheel and pedals without the environment consisting of the rest of the car body like windshield, A-pillars engine hood, etc.

The moving base has undergone very little modifications through the years, while standard digital computers have replaced the old hybrid or analogue systems. In the beginning the visual system consisted of a double beam oscilloscope that generated a simple road picture but nowadays vector generated computer graphics has been introduced. The visual display utilises a limited horizontal sight angle with the driver viewing the scenery through a collimating lens.

The second system to appear was the VTI (Swedish Road & Transport Research Institute) simulator (Figure 1b). This project started back in 1977 and the constructional period lasted till 1984 when the first research projects were carried out. In some respects the VW system influenced the design of the VTI system. The roll and pitch motions are generated very similarly but the yaw motion was discarded in favour of a large lateral motion. In order to improve the realism the simulator cab consists of a real car body (cut off behind the driver's seat) which rests on a 4 DOF (roll, pitch, heave and longitudinal) vibration table. A wide angle visual system (120° horizontally, 3 channels) complements the set-up. The extremely short transport delay is the main feature of this system surpassing all other commercial vector based system in this special area.

Daimler-Benz presented its driving simulator (Figure 1c) in 1985, [2]. The moving base consists of a large hexapod featuring 6 DOF. The visual system covers 180° horizontally and features an unobstructed view from the driver's position. The cab is a real car body not being cut off. This simulator does not incorporate a dedicated vibration table so car body roll is produced by the hexapod and roll in the visual display and vibrations are restricted to low frequencies. Current updating of this system includes
Figure 1:  

a) VW-simulator  
b) VTI-simulator  
c) Daimler-Benz simulator
the addition of large lateral motion at the base of the hexapod and a more refined visual system with more polygons and photo texture.

The Mazda Driving simulator (Figure 2a) [3] features a 4 DOF moving base (yaw, roll, pitch and lateral motion). The powerful lateral motion makes it possible to perform lane change manoeuvres with no reduction of lateral acceleration even very near the handling limit. The car cab is just a driver's seat and reminds in this respect of the VW simulator. No vibration table is used.

VTI constructed and built the TRYGG HANSA simulator (Figure 2b) [4] during 1989-91. The technical data are roughly equivalent with the VTI-system but the simulator interior has much more room and houses a complete heavy truck cab from the SCANIA range. The software enables real time simulation of heavy truck combinations comprising single trucks as well as semitrailer and full trailer combinations. All the vehicles can be equipped with up to six axles and a varying number of wheels on the axles. It is very easy to change cabs in this system in a safe and quick way.

Moving base design

The purpose of the moving base is of course to recreate the forces and accelerations in the simulator that the driver experiences during real driving. These accelerations are often of a sustained character and will last for some time (driving in a curve or circle, braking and acceleration). Quite clearly the sustained acceleration must be reproduced by a component of the gravitational force, i.e. by giving the cab a tilt in the desired direction. However the human being is quite sensitive to such tilt motion. In order to give the driver the illusion of a gradually increasing linear acceleration the tilt must be performed very slowly and smoothly encompassing only very low frequencies. In reality the accelerations are changing quickly and contain many high frequency components especially at the start of the acceleration signal. This is the basis for the idea of frequency division with the acceleration signal passing a low pass filter for the tilt motion and a corresponding high pass filter for the linear motion. The braking process is the most difficult to represent in a good way. Hard braking on a high friction surface from 70 km/h means that the retardation of the car jumps instantly from 0g to almost 1g and remains at that level for at least 2 seconds and then drops again immediately to 0g when the car has come to a full stop. The first transient means that the simulator must accelerate longitudinally with 1g, then decrease at the same rate as the slowly raising tilt motion but altogether producing the 1g level. The problem with the linear acceleration is that the simulator reaches a substantial speed which must be reduced to zero so slowly that the driver doesn't notice.

This basic problem in the braking process has a direct counterpart in the lateral direction namely entering a curve, but there are differences. Neither the onset of acceleration is so sharp nor the attainable acceleration level is so high as in the extreme braking case. Thus entering a curve should be less difficult to reproduce correctly in a simulator. Despite this, large excursion will occur in the plane even at rather moderate acceleration levels if the associated roll motion mustn't be perceptible to the driver. In
Figure 2:  

a) Mazda simulator  
b) TRYGG-HANSA simulator
the feasibility study [5] of the National Advanced Driving Simulator (NADS) a sharp entrance into a curve is simulated at the speed of 96 km/h and the final acceleration is 0.5g. Assuming that the roll rate must not be greater than 3 °/s the lateral space demand was around 26 m! At higher speeds the space demands will increase in proportion. If this is translated into the longitudinal direction, hard braking on a surface with friction level 0.5 would require about the same distance. At higher friction levels the longitudinal excursion would be correspondingly longer. It is not realistic to build a simulator with such large motion in the plane. Quite clearly compromises must be made. In the existing systems this has been addressed in the following ways

- The overall acceleration levels are scaled down
- The tilt rate is allowed to be above the level 3°/s
- Concentrating on the lateral dynamics

The trend in current design plans is to include an X-Y-motion in the plane and try to increase the value of the scale factors with the goal of approaching the desired level 1. This is evident for the SARA-project in France and the NADS-project in USA. However there will always be some manoeuvres that even the most costly and advanced systems will not be able to reproduce satisfactorily. One can only expect to increase the envelope of acceptable performance of the moving base with the new and advanced systems to come.

Visual systems

The limitations of the visual systems strongly govern the different types of studies that can be performed in a driving simulator. Constructing three dimensional objects with the aid of polygons is the basis for most of these systems. However, even when the numbers of the polygons are exceeding several thousands, drawing of a curved road and a number of other objects will relatively soon exhaust the polygons. Of course texture techniques may increase the fidelity of the picture but the basic problem still remains and that is to be able to construct a very complex scenery. The tendency in development of visual systems is that more and more polygons can be drawn offering more details. On the other hand manufacturers have not managed to significantly reduce the transport delays in these systems during the last years.

A recent report from Hughes [6] debates this development. Among several factors, added richness (texture) of the scenery increased the occurrence of simulator sickness. In fact it was argued that many factors that improve the fidelity of the simulator tend to make it worse from a simulator sickness point of view. Keeping the transport delay as low as possible is the notable exception. The impact of long transport delays is quite dramatic and increases the occurrence of simulator sickness. To some extent VTI experiences tend to support these findings. Simulator sickness is not a very pronounced
problem in the VTI simulator [7]. The extremely short time delay (very near the theoretical limit) in the visual system is the major contributing factor here. "Normal" driving on a road without sharp bends and violent manoeuvres rarely introduces any motion sickness or uneasiness. From our experience it is obvious that the strongest implication for simulator sickness is a driving task containing many sharp bends and repeated braking. Under these circumstances the shortcomings and compromises of the moving base tend to be more obvious, when one repeatedly moves outside the envelope of acceptable performance of the moving base.

VTI generally uses ordinary drivers as test subjects in our experiments. The realism of the simulator is then very important to ensure acceptance by these subjects. The real car body and the complete interior are necessary parts here. The vibration table vastly improves the road feeling of the car and we also think it is preferable to add the roll motion directly to the car.

**Software and mathematical models**

The current trend in the design of software for planned advanced simulators is to use the methodology and technique from the so called multibody programs thus relieving the user from the difficult and time consuming job of deriving the equations of motion. This development is indeed a formidable task since the simulator demands

- a complete model, i.e. all parts of the car must be modelled including engine, drive-line, suspensions, vibrations, aerodynamic forces and friction forces between tires and road

- a program that can run in real time with comparatively short integration time steps

All the existing advanced simulators use dedicated programs not based on a multibody formalism depending on the reasons stated above.

It is of course nice to be able to put together a car of well-known mechanical elements like ball-joints, springs, dampers, etc. as in the multibody formalism, but the such complex models demand many input data all of which are not easy to find. Elasticity of bushings in all directions as well as inertia tensors of all the connected masses may prove to be a difficult barrier to pass. A complex model with many input data does not necessarily increase the understanding of what to change to obtain a certain modification of the handling qualities. For the fine tuning of physical objects such programs are most suitable but probably that kind of work should rather be performed on the test track than in a simulator.

Simple models on the other hand offer an easy understanding and better control of the input data. There is no doubt that different car models can be characterized by just a few
relevant data like eigen-frequencies, relative damping, response times and so on. The
driver can readily recognize these differences and the pertinent car models in the
simulator if he has solid experience from the test track. In fact the simulator offers an
unsurpassed possibility to instantly change from one car to the other making the
comparison very easy to make and much quicker than on the test track. There the
changes may include manual modifications or even jump into another car.

The literature shows that simple simulation models can provide much insight into
vehicle handling problems. Especially in Japan many researchers use the simplest of them
all, the bicycle model, as a perfectly valid tool for studying basic concepts in vehicle
dynamics like 4-wheel steering, etc.

This does not mean that only simple models have its place in simulators. In the strive
for more complex models one should however not forget about the advantages a simpler
approach may have to offer.

**Use of simulators**

From the above discussions it should be clear that one has to be careful when
designing a simulator experiment. Particularly it is important to stay within the envelope
of acceptable performance for the specific simulator. These limits are surprisingly narrow
in the existing systems and will remain so even for the planned new simulators. Driving a
Formula 1 car at high speed on a racing track with several sharp winding curves will
always be outside the reach of even the most ambitious simulator and is certain to
produce a most unrealistic impression.

Despite all these reservations there is a multitude of projects suitable for simulator
studies. A large number of successful studies have been carried out in the VTI Simulator
and the rating of the test subjects concerning the realism of the experiment is normally
quite high. Validations between reality and simulator experiment show generally good
agreement [7].
References


