Whatever Happened to the LADS? Design and development of the new University of Leeds Driving Simulator

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Abstract

Since 1994, driving simulators have been used at the University of Leeds to undertake research into driver behaviour and transport safety. The old Leeds Advanced Driving Simulator (LADS) has now been decommissioned. This paper describes the design and construction phases of the new £1m University of Leeds Driving Simulator, which has been operational since October 2006. The paper highlights the design and development decisions made and presents technical descriptions for each of the main features of the simulator:

- Jaguar S-type vehicle cab and instrumentation
- 2.5t payload, eight degree of freedom motion system with 5m of effective stroke
- 4m spherical projection dome
- Image generation system
- Real-time Linux PC network

Résumé
Introduction

Since it became operational in 1994, the Leeds Advanced Driving Simulator (LADS) was an essential element in much of the driver behaviour and transport safety research work carried out by the Institute for Transport Studies at the University of Leeds. The simulator allowed studies to be performed in accurately controlled laboratory conditions reproducing a range of repeatable environmental, road, vehicle and traffic conditions. Prior to its decommissioning in October 2005, it was used in 25 major externally-funded projects with a combined total value of over £1.5m with sponsors including the U.K. Government Agencies, U.K. Research Councils, European Agencies and Jaguar Cars.

The simulator was a fixed-based facility, built around a complete Rover 216GTi with its driver controls and dashboard instrumentation fully operational. The projection system consisted of five forward channels, the images edge-blended to provide a near seamless horizontal field of view of 230°. A rear view (60°) was back projected onto a screen behind the car to provide an image seen through the vehicle's rear view mirror. The frame rate was fixed to a constant 60Hz. The simulator’s visual modelling, vehicle dynamics and intelligent scenario control were developed continuously using in-house expertise throughout its lifetime. Although the simulator was fixed-base, torque feedback at the steering wheel was provided via a motor fixed at the end of the steering column and a vacuum motor provided the brake pedal booster assistance.

In early 2004, the U.K. Government announced the second round of its Science Research Investment Fund. Its purpose was to contribute to sustainable research strategies and address past under-investment in research infrastructure. A bid was made to upgrade the LADS by the development of a PC network to replace the existing SGI workstations, a new vehicle cab and interior, an enhanced projection system and the addition of dynamic cues via a large amplitude motion system. The bid was successful and development of the new University of Leeds Driving Simulator began in earnest in August 2005 when orders were placed with four companies to provide these core elements of the new facility.

Design

Vehicle cab and dome

At the centre of any driving simulator are the driver and the vehicle cab in which he or she sits. The vehicle cab of the simulator is based around a 2005 Jaguar S-type, with all of its driver controls fully operational. The automatic transmission S-type was donated to the development programme under Jaguar’s Vehicle Donation Scheme. The vehicle’s internal Control Area Network (CAN) is used to transmit driver control information between the Jaguar and one of a network of eight real-time Linux-based PCs, each playing a role in the overall simulation.
The functionality of all of the main dashboard instrumentation has been retained and is controlled with messages from the PC network sent back the vehicle via the CAN. A Seeing Machines faceLAB v4 eye-tracker is also housed within the vehicle cab. The vehicle cab, including two 85kg occupants, weighs approximately 1040kg.

The Jaguar is housed within a 4m diameter, fibre-glass, spherical projection dome weighing just over 825kg (including the projectors and associated framework). In order to avoid resonant oscillations, the lowest natural frequency of the dome is designed to exceed 15Hz. As the laboratory space in which the simulator now resides is not new, the small diameter of the dome was selected in order to maximise the available motion envelope, whilst still providing a relaxed eye-point for the observer.

The dynamic platform provides the interface between the dome, the motion system and vehicle cab. It is a honeycomb composite and aluminium structure weighing just under 250kg. Built in is an emergency escape hatch and ladder.

The dome and the dynamic platform have been designed to withstand the worst-case loads imposed by the maximum linear (24.5m/s²) and angular (936°/s²) accelerations imposed should the motion system hit its end-stops at full speed.

PC network

The Jaguar’s CAN bus is directly connected to the first PC (control) in the network, communicating at 240Hz. Control receives data over Ethernet and transmits it to the second PC (dynamics), which runs the vehicle model at 960Hz. The vehicle model returns data over Ethernet to control commanding feedback that the driver seated in the cab feels (steering torque feedback and brake pedal loading), sees (full dashboard instrumentation) and hears (80W 4.1 sound system providing audio cues of engine, transmission and environmental noise).

Dynamics is connected via Ethernet to the master renderer PC, a dual core AMD Athlon 4400 with 2GB RAM and housing an nVidia FX4500G workstation class graphics card. This machine, whilst managing two of the eight visual channels, also provides the 60Hz V-Sync clock pulse that each other machines on the network use to ensure a consistent start-of-frame boundary. The FX4500G contains a hardware frame lock capability, used by the two subsequent slave renderers (slave 1 and slave 2), each also managing two of
the eight visual displays. The final two channels are rendered by two further slaves (slave 3 and slave 4), controlling the two wing mirror displays. Since slaves 3 and 4 render a less resolute display than slaves 1 and 2, they contain a lower specification FX3000G graphics card. Unfortunately, these slaves cannot be frame-locked via hardware since such communication between the two card generations is not possible within the nVidia architecture. Instead, slave 3 and slave 4 rely on master’s V-Sync signal.

**Dynamics** uses a dedicated cross-patch link to the motion computer to transmit information at 240Hz to the motion computer (**motion**), also operating using a real-time Linux protocol. **Motion**, has the role of communicating set-points to the actuators of the motion system. Specifically, it manages the protection of the input signals received from **dynamics** along with the ability to modify the various gains, cut-off frequencies and damping terms, all parameters of the Classical Washout Algorithm used within the simulator. Special effects (road rumble and bumps) are also managed by motion.

**Motion system**

The University of Leeds Driving Simulator employs an eight degree of freedom motion system. It was manufactured by Bosch Rexroth, as Renault’s ULTIMATE driving simulator, the main differences between the two systems being the shorter X-Y table available stroke (5m) but higher design payload (2500kg). Frequency response of the motion system with the full payload installed was evaluated during Final Acceptance Testing. The dynamic characteristics of the motion system are shown in Figure 2. Figure 3 shows the frequency response of the limiting degree of freedom: XY table surge.

<table>
<thead>
<tr>
<th>6DoF</th>
<th>excursion</th>
<th>velocity</th>
<th>acceleration</th>
<th>phase lag</th>
</tr>
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<tr>
<td><strong>Surge</strong></td>
<td>-408 / +307 (mm)</td>
<td>±0.8 m/s</td>
<td>±6.5 m/s²</td>
<td>7.2Hz</td>
</tr>
<tr>
<td><strong>Sway</strong></td>
<td>-318 / +318 (mm)</td>
<td>±0.8 m/s</td>
<td>±6.0 m/s²</td>
<td>7.1Hz</td>
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<td><strong>Heave</strong></td>
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<td>±0.6 m/s</td>
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<tr>
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<td>±40 °/s</td>
<td>±300 °/s²</td>
<td>6.8Hz</td>
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<tr>
<td><strong>Roll</strong></td>
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<td>±40 °/s</td>
<td>±300 °/s²</td>
<td>6.7Hz</td>
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<td><strong>Yaw</strong></td>
<td>±23°</td>
<td>±50 °/s</td>
<td>±350 °/s²</td>
<td>9.2Hz</td>
</tr>
<tr>
<td><strong>XY</strong></td>
<td>±2500 mm</td>
<td>±2.0 m/s</td>
<td>±5.0 m/s²</td>
<td>5.3Hz</td>
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<td><strong>Sway</strong></td>
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<td>±3.0 m/s</td>
<td>±5.0 m/s²</td>
<td>5.5Hz</td>
</tr>
</tbody>
</table>

**Figure 2:** dynamic characteristics of the motion system
Motion cueing

The Motion Cueing Algorithm of the University of Leeds Driving Simulator uses the Classical Washout Algorithm (Nahon and Reid, 1989; Figure 4). This algorithm is relatively straightforward when compared to other more modern techniques, but the main reason for its selection is that the system is shipped with such cueing.

With the Classical Washout Algorithm, the transition from high frequency onset to low frequency sustained acceleration needs to be performed at a rotation rate unperceivable to the occupant, approximately $3^\circ/s^2$ (Groen and Bles, 2004). However, it is well understood that vehicle accelerations tend to build up much quicker than the establishment of imperceptible tilt-coordination allows. Hence tuning the Classical Washout Algorithm is always a compromise between providing the high frequency onset response within the physical constraints of the motion system and the low frequency sustained acceleration cues without inducing a feeling of “sag” to the driver. By sag, we refer to the reduction in the perceived acceleration due to relative dominance of tilt co-ordination during the latter part of the transient region following a step control input.

Figure 4: Classical Washout Algorithm used in the simulator
Classical Washout Algorithm parameter selection is based on the worst-case scenario, dependent on the dynamic characteristics of the motion system. Since the University of Leeds Driving Simulator is used for driver behavioural studies, this gives us the advantage that scenarios can be created to fit both the research requirements and the motion limitations of the simulator. For example, three out of the five investigations commissioned to use the simulator to date have required motorway driving conditions. Tuning of worst-case acceleration is therefore much more manageable than, for example, a vehicle handling study at the extreme’s of the driving envelope. In the motorway scenarios, high levels of acceleration and rate of change of acceleration are uncommon and so the longitudinal limits have been set to 1.5m/s² in acceleration and 2.8m/s² to in braking. Lateral accelerations are limited symmetrically to 2.2m/s².

A MATLAB / Simulink model of the Classical Washout Algorithm has been developed in order to undertake off-line testing of the effects of parameter selection. Such testing ensures that the system remains within its design envelope for the selected worst-case manoeuvres. To minimise perceived tilt whilst also minimising sag, the most pertinent parameter within the Classical Washout Algorithm is the low-pass cut-off frequency of the 6DoF motion system (LP2_ms). Initial testing suggested that the optimum value in our case is 0.5Hz in both pitch and roll degrees of freedom. Whilst this still gives rotational accelerations that are comfortably higher than perceptual thresholds, this value appears to give the least “rolly” feeling to driving the simulator without overly compromising sag. Other parameters were selected to maximise washout whilst remaining within the physical limits of the motion envelope. The system has been tuned both longitudinally and laterally, resulting in parameter selection shown in Table 1.

### Table 1: Classical Washout Algorithm parameter selection

<table>
<thead>
<tr>
<th>abbreviation</th>
<th>Classical Washout Algorithm parameter</th>
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<th>lateral</th>
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<td>6DoF</td>
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<td>0.5</td>
</tr>
<tr>
<td></td>
<td>lp2_ms 6DoF 2nd order LP damping</td>
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<td>1.5</td>
</tr>
<tr>
<td></td>
<td>w_hp1_ms 6DoF 1st order HP cut-off frequency</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>w_hp2_ms 6DoF 2nd order HP cut-off frequency</td>
<td>0.35</td>
<td>0.35</td>
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<tr>
<td></td>
<td>w_hp2_ms 6DoF 2nd order LP damping</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>XY</td>
<td>w_hp1_xy XY 1st order HP cut-off frequency</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>w_hp2_xy XY 2nd order HP cut-off frequency</td>
<td>0.075</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>XY 2nd order LP damping</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>lp2_ms 6DoF 2nd order LP cut-off frequency</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>lp2_ms 6DoF 2nd order LP damping</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

### Longitudinal acceleration tuning

In a motorway scenario, a worst-case longitudinal acceleration tends to be a step brake over a duration of a number of seconds. Given the pre-selected worst-case input, the longitudinal tuning input is thus a step negative x-acceleration of 2.8m/s². The system is pre-positioned by 1m in the positive x direction, allowing an available X-table stroke of 3.5m in deceleration. Figure 5a shows the system response.
Lateral acceleration tuning

In the motorway scenario, a lateral acceleration is less likely to solely involve a single step input, as a steering input to the left often follows one to the right (or vice versa). Given the pre-selected worst-case input, the selected lateral tuning input is thus a step positive y-acceleration of 2.2m/s² followed by the same acceleration in the opposite sense some 5s later, essentially an S-shaped curve. The system attempts to pre-position prior to a curve by using the underlying knowledge of the virtual environment. Figure 5b shows the system response to this input.

In both scenarios, poor dynamic response around the 0.1-0.3Hz is as a result of low pass cut-off frequency selection and the compromises made balancing the “saggy” and “rolly” feel of the simulator when using the Classical Washout Algorithm. This is exacerbated in the second part of the S-curve, and hence such road sections are avoided in scenario development within the simulator.

Figure 5a and 5b: Bode plot and system response for a worst-case longitudinal deceleration (2.8m/s²) and lateral deceleration (double 2.2m/s² step)

Road roughness is modelled using one of the motion system’s special effects, creating a ‘random’ vertical acceleration made up of 10 sine waves and as a function of the vehicle velocity. The raw data used for the creation of road roughness is based on a spectral analysis of a typical U.K. motorway, undertaken by Dodds and Robson (1973).

Vehicle dynamics model

The real-time dynamics model is based on Newtonian mechanics and represented mathematically by 36 ordinary differential equations of motion, built up from first principles. The model is parameterised in order to describe the braking and handling behaviour of a generic, four wheeled motor vehicle with independent suspension (Sayers and Han, 1996). A non-realtime MATLAB / Simulink model of the vehicle dynamics is used to for model development and then converted into C++ code.
**Longitudinal model**

The longitudinal model, based on NADS work (Salaani and Heydinger, 1998), comprises of a number of sub-models. First, engine torque is derived from a look-up table, provided by Jaguar, describing the torque output of the S-type’s 3 litre V6 petrol engine as a function of throttle angle and engine speed. Engine torque is transmitted through a model of the torque converter. This couples the driveline axes, transferring torque as a function of the relative angular velocity of the crankshaft and gearbox input shaft. The driveline torque is then transmitted through a model of the automatic gearbox where the ratio is selected as a function of throttle position and engine speed. This torque is then passed through a final drive ratio which provides the tractive torque at each of the front wheels, allowing a calculation of wheel rotational speed and hence longitudinal tyre slip, protected against low speed instabilities by a method developed by Bernard and Clover (1995). Tyre longitudinal force is calculated as a function of longitudinal slip angle and vertical tyre loads using the Magic Formula Tyre model (Pacejka and Besselink, 1997) with tyre parameters taken from Pacejka (2002). Longitudinal load transfer is also modelled to provide an accurate representation of available vertical tyre forces. Forces and moments are collated to form the equations of motion that are used to calculate the longitudinal and vertical translational accelerations of the vehicle plus the rotational acceleration in pitch.

**Lateral model**

The lateral model starts with a calculation of the each tyre’s steering angle. The steering, power-assist and torque feedback model is based on Jaguar’s MATLAB/Simulink modelling of the S-type’s rack and pinion steering system (Burchill, 2003). The steering model is used in the calculation of each tyre’s lateral slip angle, also protected against low speed instabilities by a Bernard and Clover’s (1995) method. Each tyre’s side force and aligning moment is calculated using the Magic Formula as a function of lateral slip angle and vertical tyre force. Lateral load transfer is modelled. Equations of motion describe the translational lateral acceleration of the vehicle along with rotational accelerations in roll and in yaw.

Using vehicle parameters for the S-type provided by Jaguar Cars, the vehicle dynamics model has been compared to a similar parameter set in a 1997 version of CarSim, the University of Michigan Transportation Research Institute’s non-realtime vehicle dynamics package (http://www.carsim.com). Test manoeuvres of step braking input and double step steering input gave close correspondence to the CarSim output.

**Image generation**

A real-time, fully textured 3-D graphical scene of the virtual world is projected on the inner surface of the dome. This scene is generated by five dedicated rendering PCs on the local network. The eight visual channels are rendered at 60 Hz and at a resolution of 1024x768. The PCs are frame-locked to avoid any “tearing” of the visual image.
The projection system consists of five forward and one rear channel. Forward channels are edge-blended to provide a total horizontal field of view of 250°. The vertical field of view is 45°. The rear channel (40°) is viewed only through the vehicle's rear view mirror. The display resolution of all projected channels is 4.1 arcmin per pixel. Two 7.5” wide aspect ratio LCD panels have been incorporated into the Jaguar’s wing mirror housing displays. Each display at a resolution of 800x480.

Figure 6: exterior and interior photographs of the new University of Leeds Driving Simulator

Conclusion

Whilst the core interest of the research group, the study of driver behaviour, remains unchanged, the development of the University of Leeds Driving Simulator has improved existing capabilities and opened new research opportunities and potential collaborations, particularly in motion perception and cueing algorithm development. However, as with many facilities worldwide, much work remains in the area of simulator validation.

The simulator’s procurement costs have been made in a cost effective manner. The simulator resides in an existing laboratory space which offered over 200kW of three-phase electrical power already at hand. This significantly reduced the cost of building works. Further enabling works, including the provision of the two-storey accommodation (housing offices and control rooms), its electrical and networking services and reinforcement to the existing concrete floor, cost £131k. The vehicle cab modifications and dome came in at £360k, with the motion system costing a further £390k. The projection system, wing mirror displays and associated cabling had a price tag of £77k and an additional £10k was spent on the five image generation PCs. Peripheral items (such as the eye-tracker) along with consultants’ fees (Health and Safety obligations and structural reports) added an additional £21k.

In 2004, Kemeny introduced a tongue-in-cheek metric to assess simulator development cost in terms of financial outlay per unit weight. Not including staff time (primarily software re-development and project management), total development costs of the University of Leeds Driving Simulator were £989k including VAT (purchase tax). With the complete system, including payload, weighing 10 tonnes, we consider just under £100 per kg (on the Kemeny scale) an economical development cost for such a facility.
References


