The Influence of Motion on Handling Dynamics Analysis in Full Vehicle Simulators

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This paper aims to assess the potential of a full vehicle simulator for use in vehicle handling dynamics analysis. Ideally, a sensitive and trained test driver can feel the differences in vehicle parameter set-up using a simulator and variation experiments will ultimately help aid the design process of a new vehicle, or vehicle control system. The potential of the simulator is measured using the motion system and focuses on the feedback this provides. It is shown that the motion is important for handling analysis and its characteristic response should be tailored to suit a specific restricted handling manoeuvre by utilising specific degrees of freedom.

Topics / Driver-Vehicle Interface, Modeling & Simulation Technology, Virtual Reality

1 INTRODUCTION

Technological advances have permitted the construction of low cost six strut moving platform simulators. The recent acquisition of such a simulator in the Dept of AAE, Loughborough University, has motivated an investigation into its capabilities and limitations; the AAE simulator is shown in Fig. 1. Large-scale simulators imitate environmental influences to as high a standard as technology permits [1]. However, they still suffer limitations imposed by restricted movement, imperfect dynamic models and simplified imagery. Some handling dynamics research is performed on simulators, but with relatively limited success [2]; they are more generally used for Human Factor experiments.

This research is purely focused on analysing the usefulness of the AAE simulator as an engineering tool for handling dynamics analysis. It is desired that a (suitably trained and sensitive) driver is capable of distinguishing small changes in the transient behavior of the simulator that result from parameter changes within the vehicle dynamics model. The driver’s sensitivity clearly affects their ability to detect small variable changes. The hope is that subjective feedback from variation experiments will ultimately contribute to the design process for new vehicles, or vehicle control systems [3] that alter its characteristics [4].

The paper has three sections. Firstly, the motion and steering range and bandwidth are validated, to establish the raw performance boundaries of the rig. Secondly, a subjective assessment is conducted to determine the most influential (visual, aural and motion) component factors, and to confirm the importance of the role that motion feedback plays in the provision of a realistic vehicle response. This motivates a more detailed study of the degrees of freedom in the motion that are most valuable. The simulator’s motion characteristics are dictated by a series of high and low pass filters that are individually tuned for each degree of freedom, allowing each to be separately tuned, and also allowing subsets of these freedoms to be examined in isolation. The value of full motion and the relative influence of the loss of specific degrees of freedom is explored.

Fig. 1 Vehicle Simulator at Loughborough University

1 AVEC '06

1.1 Simulator description

The simulator is mounted on a Stewart platform providing all six degrees of freedom. The struts are high fidelity electro-mechanical motored devices and the motion has a 0.8m stroke in translation, 20m/s² acceleration, 15º rotation and 25Hz bandwidth as quoted by the manufacturer. A cogging free direct drive servomotor provides the steering feedback with a maximum 30Nm torque. Three 20" wide screen LCD monitors provide visual feedback. Although it is possible to integrate alternative vehicle model structures in Simulink, the vehicle dynamic model supplied with the simulator was used for the purposes of this paper. The precise detail of this model is proprietary, but essentially the model has 6 degrees of freedom for the body, 4 for vertical wheel motion, and 4 for wheel rotations. Simplified driveline dynamics are also emulated. The model has independent suspension for all wheels, which feature springs, dampers, anti-rollbars, rollcenters and anti-pitch characteristics. The wheels include camber, wheel hop (the wheels have mass) and toe freedoms. Tires are modeled with a relaxation length Pacejka tire model. The environment road surface information is taken from polygon data (Virtual Reality Modeling Language tracks), and splines are used to smooth out the track surface. Road surface noise is then superimposed, to combine large and small-scale road undulations. The simulator was originally specified as a racing simulation product for the games / entertainment industry. This impression has been softened somewhat by installation of a steering wheel and seat from a Jaguar XJ8, and by configuration of the vehicle model parameters corresponding to this vehicle.

2 OBJECTIVE PERFORMANCE

Here we establish the response of the simulator hardware and low level control, from the acceleration and steering torque demands generated by the vehicle model, to the forces achieved by the rig. This allows us to determine the potential response separately from the fidelity of the vehicle model. It also reveals the filtering effect of the motion cueing algorithms. A Gaussian white noise input acceleration demand, (2.1), was used to approximate the frequency response of the system in each of the three translational modes separately.

$$a_{ydem} = N\left(0, \sigma^2\right) \qquad (2.1)$$

This signal was first filtered using FFT, to limit the frequencies to a maximum of 20Hz and the magnitude then re-scaled to RMS 1m/s². Demand and response accelerations were recorded for over 300s, and 10s Hamming windows used to establish the response, using Welch's method.

The steering motor was also characterised using the same random input as for the motion response, but with the input rescaled to provide peaks at around 13Nm. The steering wheel was fixed in position using ratchet straps tied to each side of the simulator frame. Torque was recorded from the motor current.

2.1 Results

The translation acceleration responses are illustrated in Fig. 2. Each mode clearly has a minimum bandwidth of 20Hz. The Longitudinal and lateral modes have increasing gain with frequency. There is a phase lead at frequencies below 2Hz for all modes and a constant time delay of approximately 35ms. The steering torque frequency response, Fig. 3, also shows a constant time delay – though this is lower, at approx 22ms. Again the filtering / control shows gain modulation, here approximating a second order response, but again there is a minimum bandwidth of 20Hz.

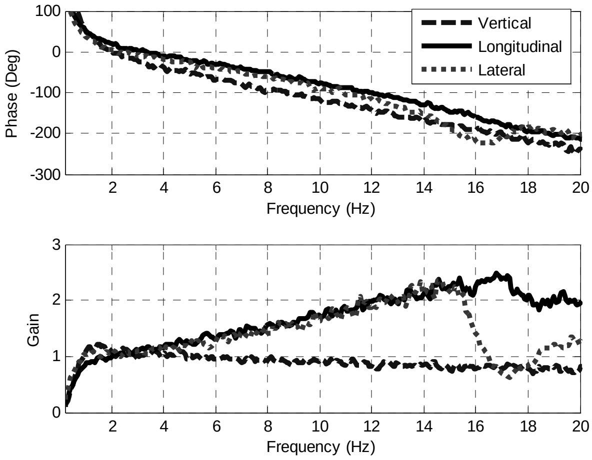

Fig. 2 Frequency response of motion platform translation acceleration

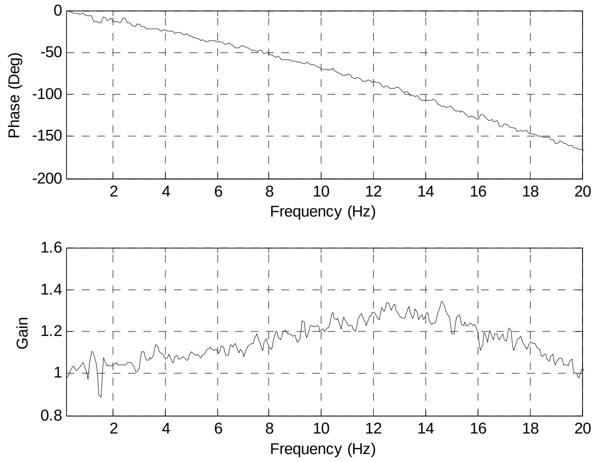

Fig. 3 Frequency response of steering torque

The enhanced lateral and longitudinal acceleration gain has been achieved by the supplier's motion cueing algorithms for improved simulation of higher frequency (e.g. collision) events, for entertainment purposes. This does not pose a problem for this research, as the gain can readily be reduced. It does demonstrate that the simulator is capable of reproducing all the required frequencies for ride and handling emulation. The constant time delays are small, and as they are coupled with low frequency phase advance, the lag around the critical 2 - 3Hz handling resonance region is minimal. The greater challenge therefore lies in the displacement range of motion. We will see in Section 4 that this fundamental limitation combined with the low pass motion centering filters present a significant limit to the magnitude and sustainability of accelerations. Further work will allow some relaxation of the filtering, to maximise use of the displacement envelope, but the remainder of this study considers how much useful feedback the driver can glean from the rig, given its excellent frequency response, but limited range.

3 ENVIRONMENTAL FACTORS

The level of realism experienced by the simulator occupant is clearly not constrained by the motion alone. It is therefore first valuable to determine the relative importance of motion, in relation to the quality of aural, visual and other haptic (in this case steering) response.

A series of tests were thus performed on a set of 12 candidates, with the test drivers covering a range of experience with the simulator, and with driving in general. The candidates were asked to drive on a test (race) track, in whatever manner they felt most comfortable. They drove first with the full simulator configuration, and then with one of the component factors listed in Table 1 restricting the simulator. After driving again with the full configuration, they then rated the percentage *improvement* in the overall realism of the driving experience achieved by recovering the lost component.

The tendency for factors to introduce or change perceived nausea is also key here – e.g. in the case of testing in the dark, a higher sense of immersion is possible, but with the risk of increased nausea. Four candidates were unable to continue with the test as they suffered from this disagreement; these are excluded from the 12 reported here. This emphasises a separate issue with the use of the simulator – that only a subset of candidate drivers are suited to making use of the facility. We shall see in Section 4 that the greater value comes from trained drivers, but duration of exposure to the simulator, and susceptibility to nausea will also restrict the candidate subset.

3.1 Results

The results are summarised in Fig. 4, where individual and average percentages are plotted. The experiment clearly shows that lack of motion is the most influential environmental factor of those tested. The background lights were clearly the least important factor but with a higher variance than the motion The importance of the remaining factors is inconclusive due to their large variance but we can say that they lie in between the background lights and motion in the rank order of priorities.

Table 1 Human factors score key

Key	
A	Background lights on
B	Audio speakers rather than headphones
C	Peripheral screens off
D	Motion off
E	Steering feedback off

The results are valuable in maximising the performance for a given application or driver. Particularly encouraging is the lower cost of retaining background lights, as this can reduce nausea in some drivers. It seems that drivers can concentrate on the displayed motion, and block out the surrounding environment in a similar way to the way one ignores the rest of the room when watching television. It is interesting that this process still seems to work in the presence of motion. A surprising result is that steering feedback is not higher in the list of priorities – though one should remember the scope of this test, using untrained aswell as trained drivers. The overwhelming importance of motion is clear, and this provides motivation to analyse how the motion configuration affects the simulated driving experience.

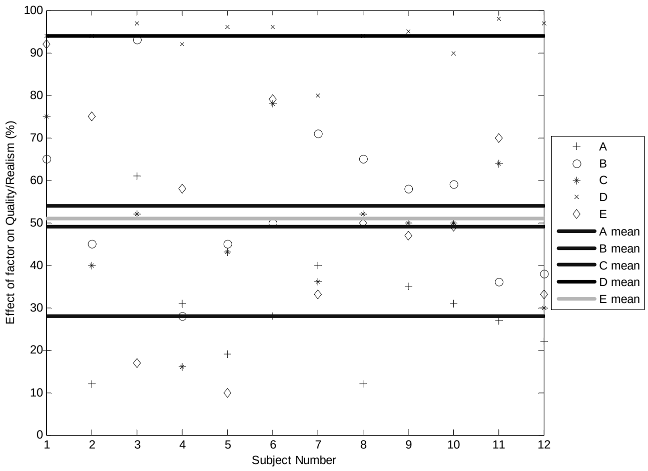

Fig. 4 Human factors scores

4 MOTION CONFIGURATION

Having established the over-riding value of motion in general, we now attempt to determine which degrees of freedom in the motion are most critical, and also the extent to which an expert driver can use these to differentiate changes in vehicle model configuration.

4.1 Method

A simple test track comprising a 1/4mile oval, with two 20º banked corners, and with a relatively rough (i.e. non-racing) surface is used. The driver was given freedom on the track allowing them to assess the vehicle characteristics by any means necessary. The only limitations were to avoid spinning or crashing the vehicle. Three vehicles were used, each being identical except that their suspension damper settings vary; these are set high, medium and low, Table 2, with either a 30% or a 70% variation being considered, to establish the driver sensitivity. Results for two test drivers will be presented – one who conducted all the tests with 30% variations, and the other with all tests based on the 70% change.

Table 2 Vehicle corner damper settings

	Damper Settings (Nms^{-1}) (±%)				
	-70	**-30**	**0**	**+30**	**+70**
Front Bump	525	1225	1750	2275	2975
Front Rebound	1275	2975	4250	5525	7225
Rear Bump	675	1575	2250	2925	3825
Rear Rebound	1500	3500	5000	6500	8500

Various motion configurations are explored, Table 3, and to ensure assessment of motion rather than visual cues, the camera position is mounted such that no part of the vehicle is visible, and with its orientation grounded to the road axis frame. The exception is Test Number 7, where no motion is provided, but the visual cues are returned to normal.

Table 3 Motion configuration tests

Test Number	Motion degrees of freedom used
1	Full Motion
2	Rotations only
3	Longitudinal & lateral translation only
4	All *except* yaw rotation
5	All *except* roll rotation
6	All *except* pitch Rotation
7	No motion, but with the camera oriented with the vehicle axis system

For each test (for each motion configuration), fifteen drives were completed. Each drive used a vehicle that was randomly selected from high, medium or low damping, without the driver's knowledge. Comparative responses were then recorded; thus after the first test the driver gave no response. After the second drive the driver was asked to comment, using only the choices in Table 4, on the vehicle's damping level compared to the previous vehicle.

Table 4 Driver descriptive choices and corresponding number

Much More	More	Similar	Less	Much Less
2	1	0	-1	-2

Each answer was then scored, based on its accuracy, using the system summarised in Table 5. This system is designed to reward accurate detection of changes in damping, and only punish incorrect results.

Table 5 Scoring of driver response, where r_i is the subjects response and $\bar{r}_i$ is the correct response.

Score	Description
2	$r_i = \bar{r}_i$
1	$r_i \neq \bar{r}_i \;\; \& \;\; \mathrm{sgn}(r_i) = \mathrm{sgn}(\bar{r}_i)$
0	$\lvert r_i - \bar{r} \rvert = 1$
-1	$\lvert r_i - \bar{r} \rvert = 2 \;\; \& \;\; \mathrm{sgn}(r_i) \neq -\mathrm{sgn}(\bar{r}_i)$
-2	$r_i = -\bar{r}_i$
-3	$r_i = -2 \times \bar{r}_i$

Each driver's testing was restricted to one day to minimise the strain on the driver and neglect any effects of taking long breaks. Therefore within each drive, a maximum of 2 minutes was allowed before an answer must be given. (Approximately 40 seconds was required to stop the simulator and change the vehicles in between each test.)

4.2 Driver screening

The motion configuration experiment also provided a natural screening process for the drivers, again highlighting the importance of using suitably sensitive and skilled test drivers. The ability of each driver to learn to tell the difference between differing vehicles ranged significantly. From early attempts at testing it became apparent that the unique response of the simulator is not something all candidates can easily adapt to, and much exposure was required before any meaningful testing within the context of this experiment could take place.

The importance of visual feedback, in terms of camera position, was highlighted early on. All initial testing kept the camera oriented with the vehicle, and the results were very promising, with average drivers being able to distinguish the difference between vehicles with ±10% damping. However, it soon became apparent that the small amounts of pitching and rolling of the camera, relative to the road, were supplying all the information the drivers required.

Without the visual rotation cues, all candidate drivers suffered a severe drop in performance, but with their inate capabilities and experience of driving having an influence on their sensitivity. On this basis the decision was made to use only two of the best drivers available; it was felt that numerous tests performed on average drivers would be less informative that a single test performed on an expert driver.

Further, these drivers were approximately normalised against each other, based on their performance in trial tests using full motion (Test Number 1). This was done by testing on progressively smaller ranges of (again random and blind) damping variations, and informally determining whether the driver felt he could satisfactorily differentiate the vehicles. Thus the normalisation is based on the driver's perception of what they could achieve, rather than what was proven through formal testing.

Driver A showed more sensitivity than any other driver during this screening process. He also had the most exposure to the simulator and motor racing experience; he performed the tests with ±30% damping. Driver B was the next most sensitive driver but had no simulator or motor racing experience; he could perform the tests with ±70% damping.

4.3 Results

The result of the formal test procedure outlined in Section 4.1 is given in terms of aggregate score for each test in Table 6. The maximum score in each test is 28.

Table 6 Driver motion configuration case study scores

Aggregate score	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Driver A (±30%)	20	12	3	9	8	10	26
Driver B (±70%)	18	14	-10	17	16	28	22

Firstly, it is enouraging to note that the informal screening process does seem to have worked in terms of the driver's relative performances on Test 1. Also note that neither of the Test 1 scores is perfect, so we are assessing the drivers close to the limit of their capabilities. The score for Test 7 shows how both drivers improved, getting closer to a perfect score when the visual cues are replaced.

The key result is the reductions of score between Test 1 and 2, and between 2 and 3. In Test 2, all translation cues were removed, and the performance of Driver A is almost halved; less of a reduction is seen for Driver B. In Test 3 the results for longitudinal and lateral translation cues are very poor – Driver B apparently even being misled by the presence of these motions only (though we must of course concede that these are case studies, and not thorough statistically proven results). The conclusion is that loss of the rotations causes a reduction in performance, but loss of vertical cues leads to a more significant reduction, and with only lateral and longitudinal cues, neither driver could perform.

The only difference between Tests 2 and 3 is loss of vertical motion, so ride perception is the most significant factor; this is an entirely obvious and expected result. The more interesting result is that rotations provide the next most important modes, with lateral and longitudinal motion being relatively useless – at least for our drivers, and the perception of damping. Clearly we would expect the roll and pitch modes to provide good feedback damping, but we might also have expected lateral transient (translation) lags to provide clues.

Test 4, 5 and 6 are relatively inconclusive in their target – to determine which single rotational mode is most important (taking the Driver B, test 6 maximum score as rather an outlier). Most surprisingly, loss of yaw seems to reduce the score by a similar amount to loss of pitch or roll.

4.4 Simulation range

The results may be largely explained by the simulator's range in each degree of freedom. The ±15º capability in the roll and pitch degrees of freedom is ample for the expected ±5º experienced on typical road vehicles traveling on a level surfaces. The ±0.4m deflections is also sufficient for the expected ±0.1m vertical displacement on typical road vehicles. The same limitations apply to lateral and longitudinal displacement however, and these are clearly not sufficient.

Fig. 5 illustrates the point further, comparing lateral acceleration measurements taken from a test vehicle with those from a similar vehicle on the simulator. The test is a double lane-change, undertaken at approximately the same speed (though the inputs are not identical). The lateral displacement of this manoeuver is approximately 3.5m. Therefore the simulator can only be expected to achieve approximately one eighth (0.4/3.5) of the acceleration seen in the vehicle if it attempts to match the lateral acceleration profile. This could be improved to approx. one quarter if the simulator were offset at the start of the manoeuvre, and the low pass, deflection centreing function of the motion cueing algorithm was removed.

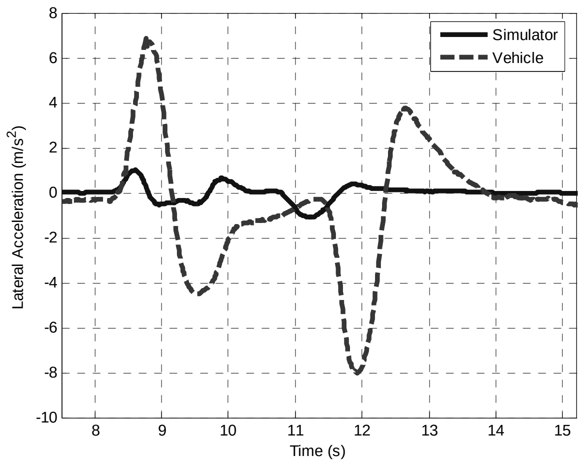

Fig. 5 Comparison of measured simulator and vehicle lateral acceleration for a double lane change manoeuvre

The considerably lower force feedback generated at these fractions makes it very difficult to simulate the lane change manoeuver. It can also be seen in Fig. 5 that the response profile is quite different. This is an accumulation of factors that include differences in steer input, slight path differences and the motion cueing algorithms. Note that the simulator performs a positive acceleration correction at around 10s however – this is to correct the position of the simulator buck, and it is not a physically correct cue.

One conclusion we might sensibly make is that, whatever testing the simulator is required to undertake (and this might usefully be made very specific – eg in offsetting for preparation of a lane-change), no accelerations are applied which are in the opposite sense to the driver's expectation. Achievement of this requires either very serious limitation of the manoeuvres, or of the accelerations induced on the platform, but the benefit of avoiding wrong motion is highly likely to outweigh the reduction of magnitude in correct motions. Also it should be borne in mind that the pitch and roll rotations induce lateral and longitudinal accelerations of the driver's head which are correct, and may be of sufficient value despite the loss of gross vehicle translation accelerations.

5 CONCLUDING REMARKS

For a fixed base Stewart platform full motion simulator the most influential factor in the human perception of handling characteristics is the transient motion of the camera relative to the road. Aside from this, the motion is the most influential factor. The longitudinal and lateral translations of the platform were the least influential degrees of freedom, for the damping variation tests considered.

One could make the broad conclusion, that the motion system in its current state should not be considered as a good tool for handling analysis at all, at least with the drivers that were available for this research. With a large (±30%) variation of damping and full motion it becomes difficult to distinguish between vehicles and requires an experienced driver with much exposure to the simulator for success. Any less damping variation certainly required a more sensitive driver than was readily available. Experience tells us that the handling of vehicles with ±30% damping would feel very different when driven. Based on this it becomes difficult to see how the current state of the simulator could be used for general handling analysis.

However, the beneficial influence of motion in general, and the satisfactory bandwidth of the motion and steering feedback, is positive. In future research the filtering characteristics will be modified to suit the specific driving scenario. Based on this the authors believe that there is still much potential for using this simulator for vehicle dynamic analysis, provided there is a restriction to the handling manoeuvres tested, and careful restriction of the longitudinal and lateral translation modes of motion. Further, the simulator's value for assessing vehicle ride is likely to be high.

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