

# Leveraging driving simulator advances in early phase vehicle development - Partitioning of vehicle states for enhanced motion feedback

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## ABSTRACT

This paper presents a novel approach to motion cueing in moving base driving simulators (MBDS) for early-phase vehicle development. Traditional motion cueing algorithms (MCAs) rely on high-pass filtering of global vehicle states, which can reduce realism and limit the effectiveness of simulation-based subjective evaluations. The proposed method partitions vehicle motion into two components: terrain-induced (global) and vehicle-induced (local) motion. This allows for selective filtering, preserving low-amplitude high frequency vehicle responses while attenuating low frequency high amplitude terrain effects which does not fit in simulator workspaces. Two partitioning strategies are explored: a velocity-based method for pitch motion and a more general ground-plane estimation using tyre contact points. Simulation results demonstrate improved correspondence between actual and simulated pitch and roll motion, particularly in vehicle-induced motion such as braking or turning. The approach shows potential to enhance motion feedback without exceeding platform limits, enabling more effective virtual prototyping and subjective driver feedback early in the design process. Future work includes implementation in real simulators. The method supports sustainable vehicle development by reducing reliance on physical prototypes and accelerating iterative design.

## 1. INTRODUCTION

Sustainable vehicle development must balance environmental, economic, and social objectives while ensuring technological feasibility and competitiveness. The concept phase is critical for embedding sustainability, yet development often relies on incremental improvements rather than transformative changes. A key challenge is the reliance on subjective assessment for evaluating vehicle dynamics and comfort, which traditionally requires physical prototypes, limiting rapid prototyping [1].

Moving base driving simulators (MBDS) address this challenge by enabling early phase virtual testing and validation [2]. MBDS allow for evaluation of new concepts before physical prototypes are built [3]. This enhances resource efficiency, shortens development cycles, and facilitates early subjective evaluation of sustainability-driven designs.

A limitation of simulation-driven development is the subjective validation of motion cueing algorithms (MCAs), which rely on physical prototypes for tuning, hindering virtual-first development [1]. To close the loop on virtual prototyping, an objective MCA approach is needed, enabling early-stage assessments without physical testing and ensuring correlation between simulator and vehicle. By integrating virtual development and sustainability-driven design, objective MCA validation could accelerate the development of resource-efficient vehicles.

## 2. MOTION CUEING

Motion cueing is necessary in MBDS due to limited workspaces [4,5]. To handle the limitations, high-pass filters are used to remove large vehicle motions, which are on a global scale, while preserving smaller amplitude high-frequency content for driver perception [6]. A major challenge is maximising motion fidelity while avoiding simulator constraints when undergoing filtering [7].

A novel method to retain important motion for vehicle dynamics cueing was presented by Bruschetta et al. [8] where the vehicle yaw rate  $\dot{\psi}$  was partitioned into the path yaw rate  $\dot{\gamma}$  and the slip angle rate  $\dot{\beta}$ . Since  $\gamma$  represents the global motion, it requires filtering to avoid workspace limitations, whereas  $\beta$ , normally confined within  $\pm 10^\circ$ , can be directly fed to the simulator without filtering, improving motion quality and simulator-vehicle motion correlation [9][10]. By avoiding filtering, low-frequency content of  $\beta$  is kept

intact for the driver in the simulator to experience. This low-frequency content has a significant effect on the perceived fidelity and motion quality [10].

In this work, an effort is made to extend this approach to several DOFs. The motivation to extend this methodology to more DOFs is straight forward. By partitioning the states into quantities that are related to the global motion of the vehicle, which is only path dependent, and quantities that are related to the vehicle's states, which are dependent on the driver's input, improvements are possible: Ground vehicles motions are in general limited in relation to the local path. As mentioned, lateral slip is commonly limited, and so are roll motion relative to ground, pitch motion relative to ground and the centre of gravity height relative to ground.

To estimate pitch angle relative to ground during straight ahead driving, a naïve approach is to use the vehicles vertical heading as a proxy for ground heading. Thus, a vertical body slip angle  $\phi$  can be defined by vehicle's z-velocity  $v_z$  and x-velocity  $v_x$ :

$$\tan \phi = \frac{v_z}{v_x} \quad (1)$$

This would be defined as the body angle of attack in aviation terms. Thus, pitch angle can be partitioned into:

$$\theta = \alpha + \phi \quad (2)$$

where  $\alpha$  represents pitch angle of the terrain, while  $\phi$  captures vehicle pitch motion relative to local terrain. Filtering  $\alpha$  while preserving  $\phi$  allows for realistic simulation of local pitch dynamics:

$$\theta_s = G(s)\alpha + \phi \quad (3)$$

where  $\theta_s$  is the pitch angle of the simulator,  $G(s)$  is a high-pass filter where  $s$  is the Laplace operator. This is compared to the industry standard approach of filtering  $\dot{\theta}$  directly:

$$\theta_s = G(s)\theta \quad (4)$$

To illustrate this strategy, a simulated vehicle was tested on a track with a crest into a 5% slope. At 550-630 meters, the driver applied 0.6 G braking (Figure 1).

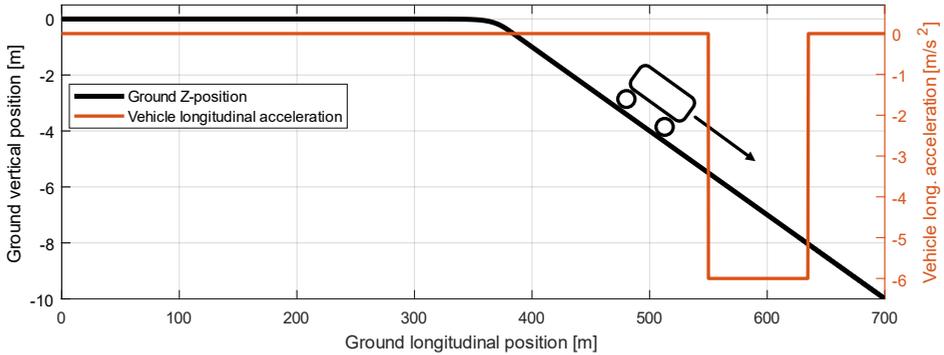


Figure 1: Track and acceleration input for pitch simulation

The results (Figure 2) show that between 6–10 seconds, both partitioning and standard filtering methods performed similarly, with an initial pitch onset followed by washout. However, between 11–14.5 seconds, when braking occurs, the partitioning method retained pitch cues 1:1, whereas the standard method washed out pitch, reducing realism. The bottom right graph highlights how the partitioning method preserves vehicle pitch relative to the ground, improving driver perception of longitudinal dynamics demonstrating its advantage for early-phase evaluation.

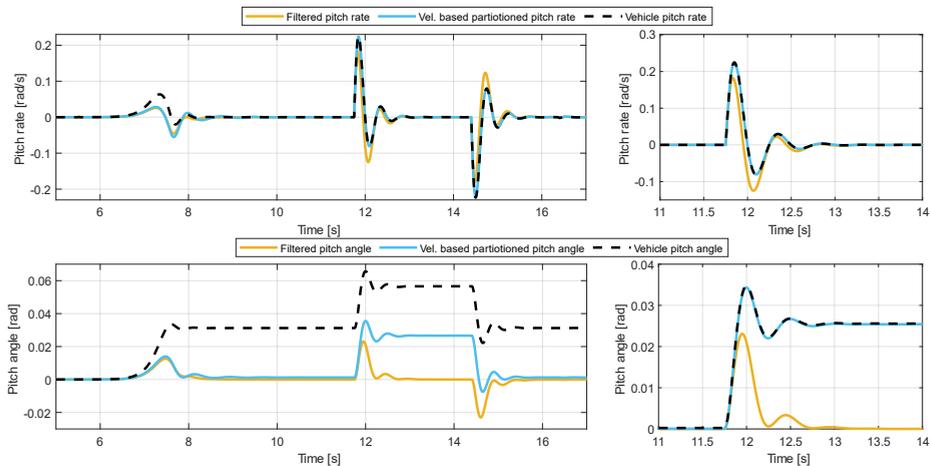


Figure 2: Results of simulation with pitch rate (top) and pitch angle (bottom). Note that bottom right plot illustrates vehicle pitch angle relative ground.

The scope of the velocity-based method is limited to pitch, as it does not allow for estimation of vehicle roll angle relative to ground nor vehicle vertical

motion relative to ground. For vehicle roll relative to ground, a velocity-based method is difficult to obtain as vehicle to ground roll is not necessarily observable, as it requires  $v_y$  to obtain how the vehicle slides on the ground surface in the global frame of reference. Lateral velocity  $v_y$  is a state that is rapidly changing, and for a neutral steer car it is zero (or close to zero) in steady state and hence the direction of  $V = [v_x, v_y, v_z]^T$  is not suitable to be used to find a proxy for ground roll. It is thus necessary to find another method to estimate the ground plane.

One possible method is to use the tyre-ground contact points as ground probes, to estimate the local ground states. The methodology is illustrated in Figure 3, with a four wheeled vehicle rolling over uneven ground.

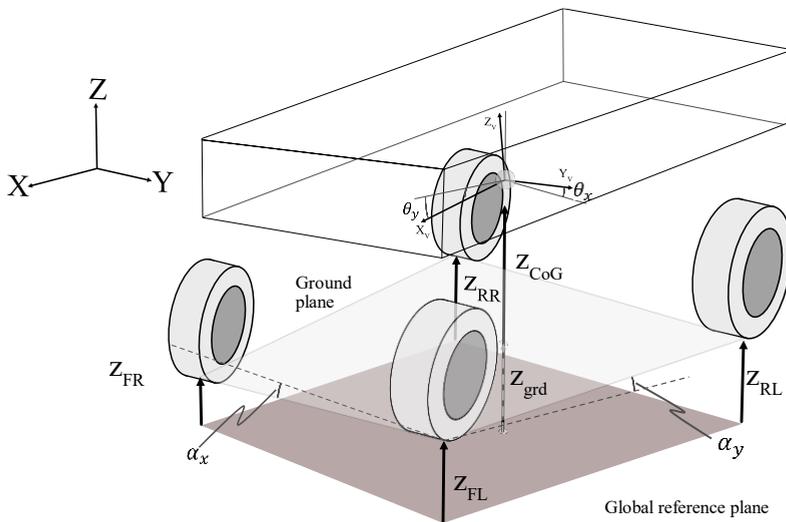


Figure 3: Illustration of a four wheeled vehicle rolling on a road with road roll-angle  $\alpha_x$ , and road pitch-angle  $\alpha_y$  and height  $z_{grd}$  at the point of interest (in this case CoG).

The ground is assumed to be a flat plane with the equation based on the wheel  $x_{ij}$  and  $y_{ij}$  positions relative to the point of interest:

$$z_{ij} = x_{ij} \tan \alpha_x + y_{ij} \tan \alpha_y + z_{grd} \quad (5)$$

The vehicle in this case has four wheels, and hence the wheel contact points overdetermine the plane. A least square approach to estimate the plane states is therefore used. The problem can be formulated as:

$$A_{whl} \begin{bmatrix} \tan \alpha_x \\ \tan \alpha_y \\ z_{grd} \end{bmatrix} = [z_{FL} \quad z_{FR} \quad z_{RL} \quad z_{RR}]^T = z_{whl}$$

where  $z_{whl}$  is the wheel z-coordinates and  $A_{whl}$  is the coefficient-matrix:

$$A_{whl} = \begin{bmatrix} x_{FL} & y_{FL} & 1 \\ \vdots & \vdots & \vdots \\ x_{RR} & y_{RR} & 1 \end{bmatrix} \quad (7)$$

The least square involves a pseudo inverse of the  $A_{whl}$  matrix. The matrix is static and hence the pseudo-inverse can be calculated offline. The least square approach is therefore suitable for real-time calculations and the ground plane states can be solved as:

$$\begin{bmatrix} \tan \alpha_x \\ \tan \alpha_y \\ z_{grd} \end{bmatrix} = (A_{whl}^T A_{whl})^{-1} A_{whl}^T z_{whl}$$

Even though the ground states are filtered due to the least square fitting, the ground states are inherently carrying noise, as the ground coordinates can change in vertical direction without any limit. The idea of partitioning the states is to filter out low frequency content that is contained in the global motion of the vehicle, Thus, before calculating the vehicle relative to ground states, the ground states are low-pass filtered.

The low-pass filter used in this work was calculated to be a first order filter based on the kinematics of a rolling vehicle, on uneven ground. The assumption is that any ground state will change fully over the length of the wheel base, denoted  $L$ , given a step input. Thus, the following first order filter is used and an example for pitch is presented below and illustrated in Figure 4:

$$\alpha_{y,0} + \dot{\alpha}_y dt = \alpha_{y,1} \rightarrow dt = \frac{L}{v_x}$$

$$\dot{\alpha}_y = \frac{v_x}{L} (\alpha_{y,1} - \alpha_{y,0}) \tag{9}$$

$$\alpha_{y,0} = \frac{\frac{v_x}{L}}{s + \frac{v_x}{L}} \alpha_{y,1} = LP_y \alpha_{y,1} \tag{10}$$

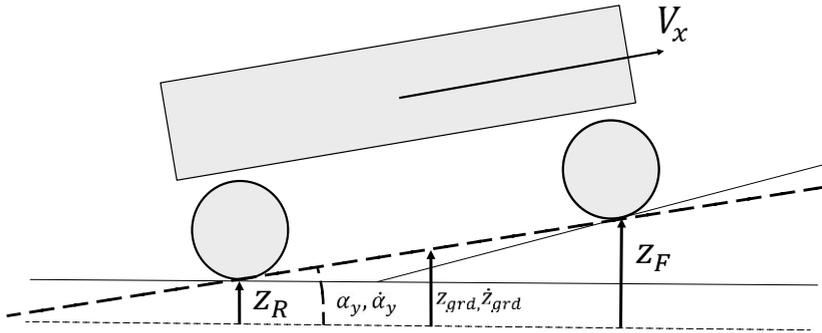


Figure 4: Illustration of a two-axle vehicle rolling on an undulated road, highlighting the spatial filtering of the ground due to the wheel base.

where  $LP_y$  denotes the resulting low pass filter. Now the estimated vehicle roll angle  $\varphi$ , vehicle pitch angle  $\phi$  and vehicle CoG height relative to ground  $h_{grd}$  can be estimated:

$$\begin{aligned} \theta_x - LP_x \alpha_x &= \varphi \\ \theta_y - LP_y \alpha_y &= \phi \\ z_{CoG} - LP_z z_{grd} &= h_{grd} \end{aligned} \tag{11}$$

The roll, pitch and vehicle vertical states have now been partitioned into a ground state which is related to the local terrain, and a vehicle state relative to this local terrain.

The terrain related states are then high-pass filtered to filter out the global motion, and the simulator states can now be calculated as:

$$\begin{aligned}\theta_x^s &= \varphi + G(s)_x LP_x \alpha_x \\ \theta_y^s &= \phi + G(s)_y LP_y \alpha_y \\ z^s &= \Delta h_{grd} + G(s)_z LP_z z_{grd}\end{aligned}\tag{12}$$

where  $G(s)$  is a high-pass filter. In this work a second order high-pass is used with a frequency of 0.65 Hz and a gain of 1.  $\Delta h_{grd} = h_{grd} - h_{grd}^{static}$ , i.e. how much the CoG (or the point of interest) is moved relative to ground compared to when the vehicle is static in stand-still.

Ideally, the filtered quantities are only related to the terrain, the velocity the vehicle has been driven with over the terrain, and the dimensions of the vehicle. The configuration of the vehicle should ideally only affect the parts which are not high-pass filtered: e.g., with softer springs, the vehicle will have a larger roll and pitch angle relative to ground, however the ground roll and pitch angle will not change. Hence, by partitioning the states and avoid high-pass filtering the vehicle related states, the possibility to test vehicles in the simulator should be enhanced, even when driving on tracks which has terrain which is significant to the workspace of the simulator (i.e. test tracks which are not flat).

For reference,  $G(s)$  is applied to the total roll and pitch state according to equation (4).

### 3. RESULTS

A full car was used to test the outlined methodology, using tyre contact points to probe the ground. The same manoeuvre as illustrated in Figure 1 was applied to validate the method in comparison with the velocity-based method.

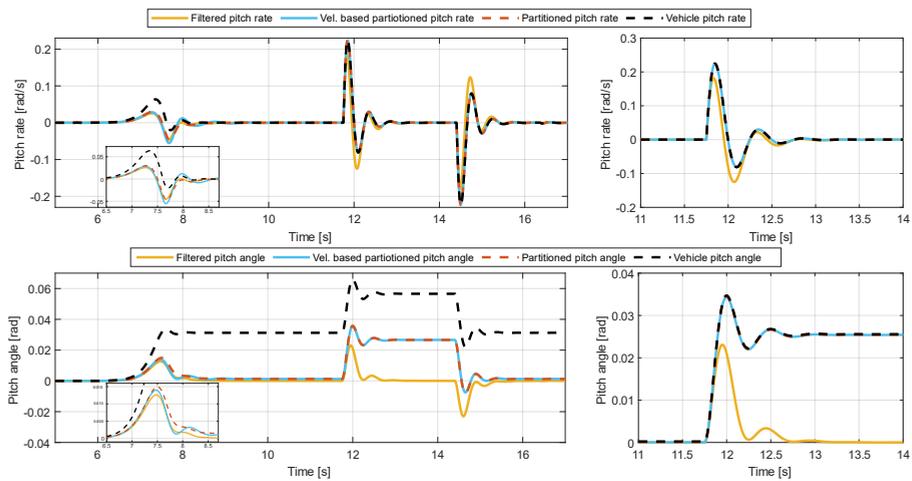


Figure 5: Pitch feedback for a full-car running down a hill and subsequent braking at  $6 \text{ m/s}^2$

The results shows that probing using the tyres produced similar performance as with using the velocity-based method, showing the same enhancements especially regarding vehicle motion which is independent of ground (pitch due to acceleration) showing one-to-one correlation in this case. A significant improvement compared to classic high-pass filtering.

To showcase the method for more degrees of freedom, a manoeuvre using a road-step on the left side was used, followed by a right turn at  $6 \text{ m/s}^2$ . The rational for this manoeuvre was to trigger both roll, pitch and vertical motion of the vehicle. The manoeuvre was conducted at highway speed at  $30 \text{ m/s}$ .

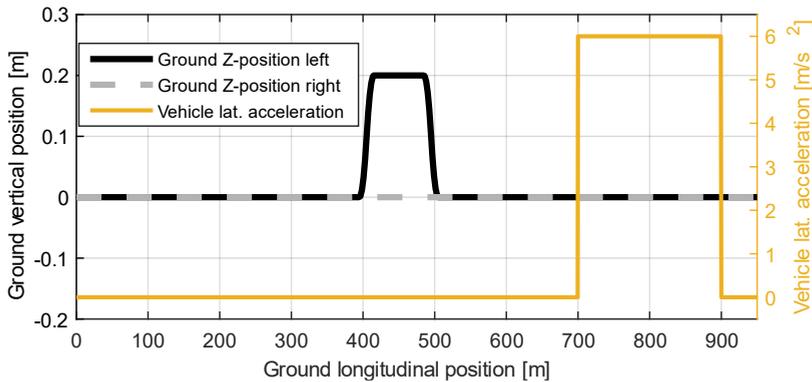


Figure 6: Manoeuvre with a road-step on the left side of the car, followed by a right turn at  $6 \text{ m/s}^2$

The results from the road-step manoeuvre are presented for pitch and roll in Figure 7 and Figure 8 respectively. The road-step does not contain any steady state pitch, but rather creates a transient manoeuvre with subsequent oscillations due to a slightly underdamped vehicle. For pitch, it is clear that partitioning the state has possible advantages even during transient events, as it can follow the vehicles oscillations close to 1-to-1 in such an event. The reason for this behaviour is that with the use of a low-pass filter according to equation (11), highly transient events will be attributed to the vehicle state ( $\varphi, \phi$  and  $h_{grad}$ ), as only the low frequency content of the ground state ( $\alpha_y, \alpha_x, z_{grad}$ ) is deducted from the global vehicle motion ( $\theta_y, \theta_x, z_{COG}$ ). This highlights one key benefit of the method.

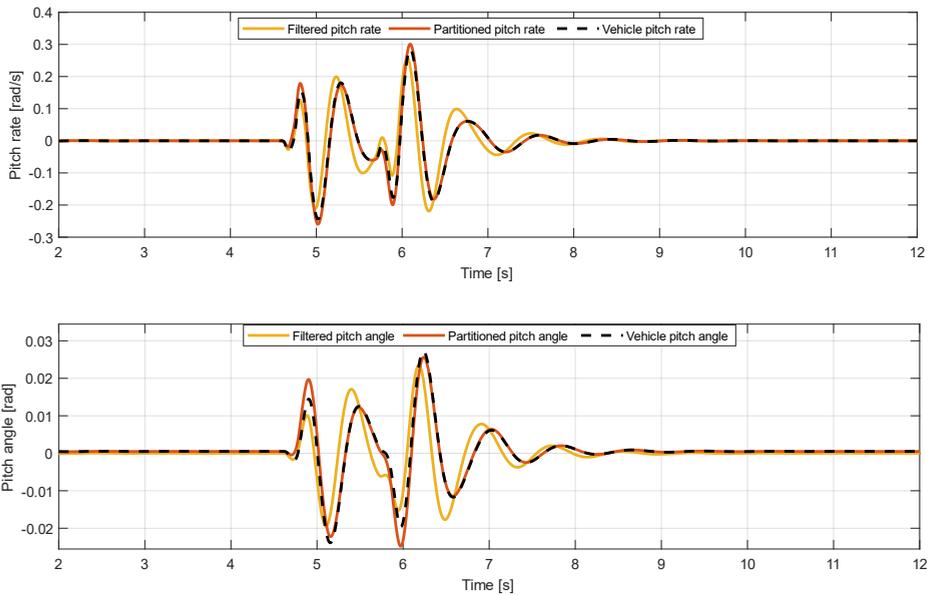


Figure 7: Pitch rate and pitch angle during road-step manoeuvre

For roll, there is a steady state roll angle when the vehicle is driving on the road-step on the left side. The results show once again that portioned roll states stay closer to the actual vehicle roll states compared to the filtered reference. Specifically, the roll state has a smaller false roll angle cue at ~5.5 seconds, as it contains some of the vehicle roll angle (which is slightly positive due to the incline from the road-step). Further, it follows the roll rate to a higher degree around 5.5 seconds, as well as around 6.5-7 seconds, when oscillations from the vehicle itself is the dominant roll cue after going down the road-step.

At 8 to 11 seconds, when the vehicle is undergoing cornering, and the roll angle is acceleration induced, the partitioned roll states follow the vehicle roll states exactly, highlighting the advantage of partitioning of states to improve simulator motion. The added benefit of tilting the simulator in steady state during cornering is also to be mentioned, giving a steady state lateral acceleration of the driver, in this case of about  $0.6 \text{ m/s}^2$ , which is not insignificant (not shown, but can be deduced from the roll angle).

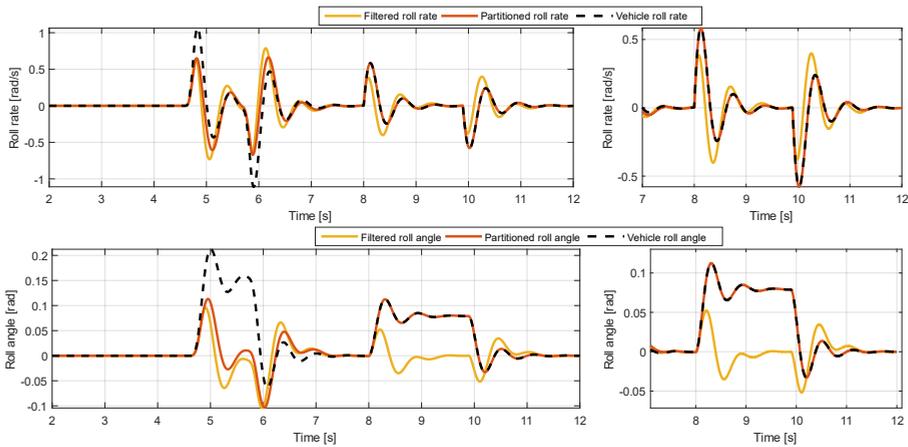


Figure 8: Roll rate and roll angle during road-step manoeuvre

## 4. DISCUSSION AND CONCLUSION

Simulators are a key element in resource efficient vehicle development, as it allows for a faster rate of development while it reduces resource heavy physical testing. For simulators to be a good complement and in some cases a successful substitute to physical testing, the motion cueing must represent the actual vehicle motion well. This is one of the challenges of simulators which has limited their use.

In this work, a novel methodology for motion cueing is presented which is based on partitioning global vehicle states in ground states and vehicle relative-to-ground states. The fundamental idea is to filter out the ground states which can be large, while retaining vehicle-to-ground states which are small enough to fit in the workspace of a simulator.

Two methodologies to partitioning the states are presented in this work, the first using velocity-based partitioning, inspired by the work of Bruschetta et al. [1], which is limited to pitch only. A further development of the methodology is also presented, using tyre contact point probing to estimate ground states which then is used for partitioning of pitch, roll and vertical motion.

Both methodologies show promising results. The velocity-based method has similar performance as the classic filtered method for pitch induced by ground and improves the performance significantly with pitch induced by acceleration. The ground state methodology indicate that it can improve cueing for pitch feedback compared to classic filtered cueing, both illustrated during a

slope and brake manoeuvre, as well when running over a road-step where the cueing allows close to 1-to-1 feedback in the simulator. For roll, the methodology shows significant improvements both during ground-induced motion as well as vehicle induced (turning) motion.

Future work should be to implement the strategy in a driving simulator to be evaluated by professional test drivers. Further, partitioning could possibly be extended to aviation as well, e.g. separating angle of attack from airplane pitch, and separate a turn into a coordinated turn and a relative roll angle.

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