**Supplementary material**

Study: Emergency braking at intersections: A motion-base motorcycle simulator study

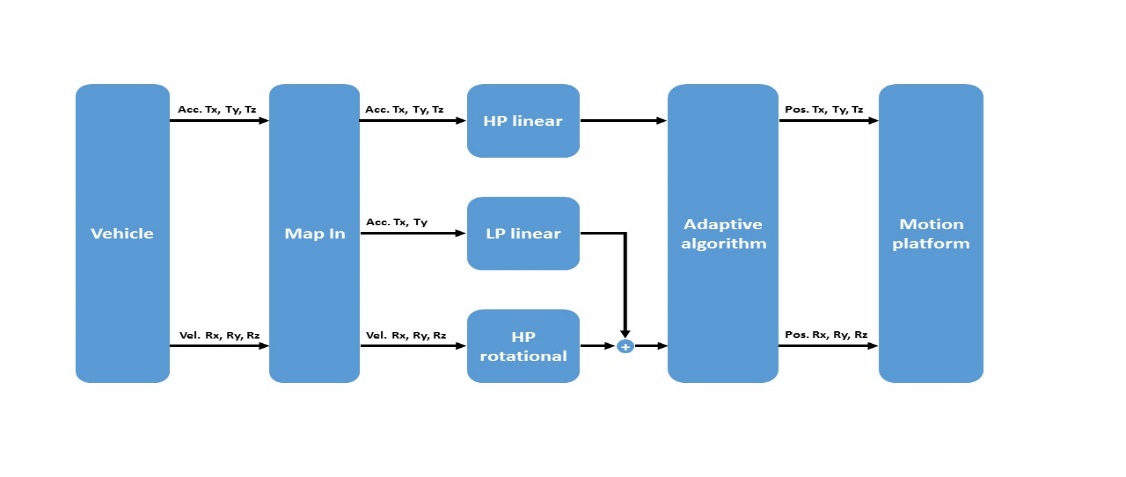
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**Motion cueing algorithm**

The motion cueing adopted during the experiment is an adaptive filter-based algorithm. The logic of the motion cueing algorithm is shown in Figure S1.



*Figure S1*. Scheme of the adaptive motion cueing algorithm. *Abbreviations*. ‘Acc.’ – acceleration: first order time derivative of the velocity; ‘Pos.’ – position; ‘Vel.’ – velocity: first order time derivative of the position; ‘Tx, Ty, Tz’ – translational motion along X, Y and Z directions, respectively; ‘Rx, Ry, Rz’ – Rotational motion along X, Y and Z directions, respectively.

### *Vehicle*

In this block, the vehicle dynamics is computed and the linear accelerations and angular velocities at the center of gravity of the vehicle are extracted and passed to the next block of the motion cueing algorithm.

### *Map In*

The Map In block takes as input the linear accelerations and angular velocities of the vehicle coming from the Vehicle block and implements different functions to adapt the input before to pass them to the next blocks. First, it includes a first-order low pass filter to remove the high-frequency content of the signal. Second, it implements an onset limiting to avoid step accelerations coming from the vehicle model. Then, it scales the input signals and finally, the most important function of the Map In block is the transformation of the acceleration’s reference system. The vehicle model has two main reference systems: the center of gravity of the vehicle (CG) and the reference frame of the rider’s head (CRP). The vehicle accelerations and angular velocities are computed from the Vehicle block in the CG reference frame, but the targets for the motion cueing are the accelerations and angular velocities in the CRP frame. By knowing the position of CRP with respect to CG, a kinematic transformation is performed which translates the input to the CRP frame.

*Table S1*. Parameters of the Map In block.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter name | Value | Unit | Remarks |
| Input filter omega | 120 | rad/s | Cut-off frequency of the first order low-pass filter |
| Max onset limit linear accelerations | 100 | m/s³ | Linear acceleration rate limit value |
| Max onset limit rotational accelerations | 100 | rad/s³ | Rotational acceleration rate limit value |
| Max onset limit rotational velocities | 100 | rad/s² | Rotational velocity rate limit value |
| Position CG to CRP: x | 0 | m | Location of the CRP with respect to CG |
| Position CG to CRP: y | 0 | m |
| Position CG to CRP: z | 1 | m |
| Acceleration X gain | 0.25 |  | Gain of the input linear acceleration |
| Acceleration Pitch gain | 0.5 |  | Gain of the input angular acceleration |
| Velocity Pitch gain | 0.5 |  | Gain of the input angular velocity |

### *High-Pass (HP) linear*

The linear accelerations are passed to the HP linear block, which is responsible for removing the low-frequency content of the signals which would lead to displacements exceeding the motion range of the platform. Besides filtering the input signals with a first order high pass filter, the HP linear block also limits the output values to ensure that the output never exceeds the maximum value.

*Table S2.* Parameters of the HP linear block.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter name | Value | Unit | Remarks |
| HP filter omega | 3 | rad/s | HP filter frequency |
| Accelerations output limiter | 3 | m/s² | Limit value of output accelerations |

### *Low-Pass (LP) linear*

Longitudinal and lateral accelerations are passed to this block, which is responsible for extracting only the low-frequency content of the signals, the so-called sustained accelerations, by means of a second order low pass filter. The perception of sustained acceleration is reproduced by tilting the motion system to certain roll and pitch angles (this is also called tilt coordination). The LP linear block scales the input accelerations with a fixed gain and ensures that the output acceleration does not exceed a limit value.

*Table S3*. Parameters of the LP linear block.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter name | Value | Unit | Remarks |
| LP filter omega | 3 | rad/s | Cut-off frequency of the second order low pass filter |
| LP filter zeta | 0.9 |  | Filter damping |
| Accelerations input gain | 0.5 |  | Gain of the input accelerations |
| Accelerations output limiter | 2 | m/s² | Limit value of output accelerations |

*High-pass (HP) rotational*

The angular accelerations are filtered with a third-order high pass filter. The filter used has a transfer function of the form shown in Equation S1. The output is also scaled and the resulting angular accelerations are limited.

*Equation S1*. Third order high pass filter used for the HP rotational block.

*Table S4.* Parameters of the HP rotational block.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter name | Value | Unit | Remarks |
| HP filter omega 2 | 2 | rad/s | Cut-off frequency of the HP filter (2nd order) |
| HP filter omega 1 | 1 | rad/s | Cut-off frequency of the HP filter (1st order) |
| HP filter zeta | 0.8 |  | Filter damping |
| Accelerations input gain | 0.5 |  | Gain of the input accelerations |
| Accelerations output limiter | 3 | rad/s² | Limit value of output accelerations |

### *Adaptive algorithm*

The adaptive algorithm takes as input the signals generated by the HP linear and HP rotational blocks and modifies them according to the adaptive cueing strategy. The principle of the adaptive algorithm is to introduce additional washout on the linear displacements to ensure that the platform stays within its workspace. Washout is a term used to identify a motion gradually returning towards the center position of the platform. The washout motion is, therefore, a false motion cue, which is necessary to avoid the physical limitations of the motion system. The advantage of an adaptive cueing algorithm is that when the required motion is small, the motion system will use more of the available workspace to reproduce more accurately the motion reference. While, when the required motion is very large, the adaptive algorithm will reduce the linear platform displacements keeping the system within its boundaries. The way the additional displacements are calculated is by minimizing a cost function. The factors involved are actuator position (large positions need to be avoided due to limited actuator lengths), actuator velocity (high velocities require large actuators positions, which is an issue due to limited length), and washout acceleration (washout is a false cue and needs to be minimized). The tuning of the adaptive algorithm requires a trade-off between these three quantities.

### *Motion platform*

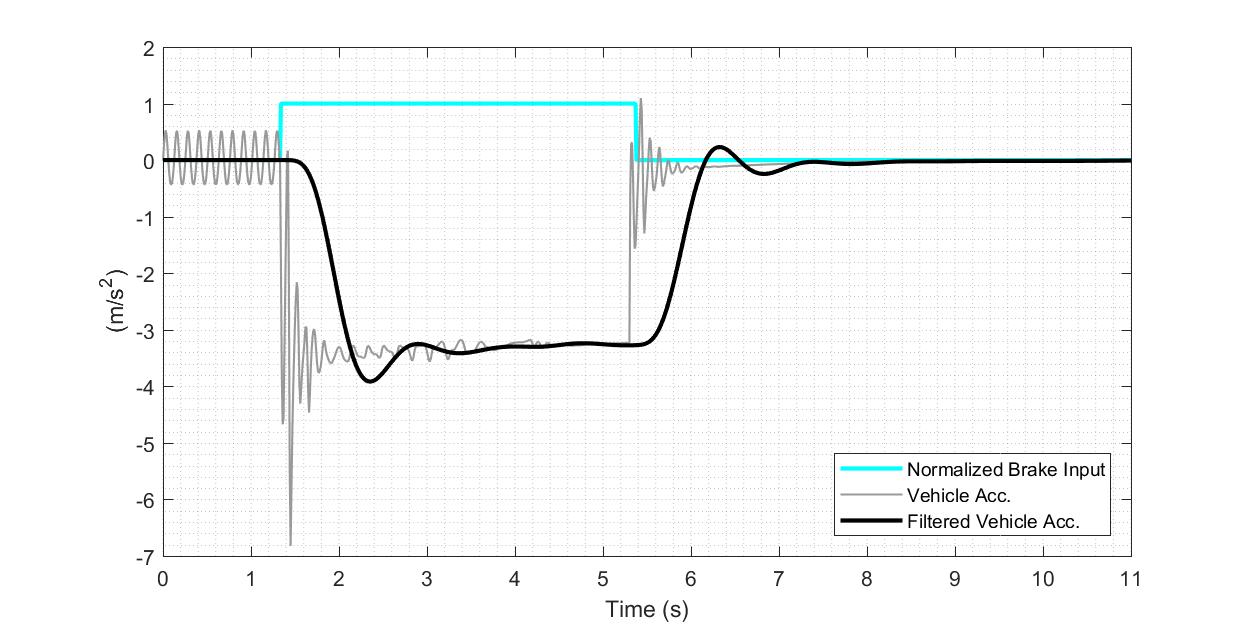
On the motion system, there are other three reference systems: one positioned at the center of the fixed based (FPC), one at the center of the moving base (MPC) and another one at the head of the simulator rider (RRP). The positions and orientations for the motion system are computed in the RRP frame. The position of this frame is defined with respect to the MPC frame and it depends on the position of the simulator rider. Another kinematic transformation needs to be applied here to convert the computed positions and orientations from MPC to RRP.

*Table S5.* Parameters of the Motion platform block*.*

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter name | Value | Unit | Remarks |
| Position MPC to RRP: x | 0 | m | Location of the RRP with respect to MPC |
| Position MPC to RRP: y | 0 | m |
| Position MPC to RRP: z | 2 | m |

### *Motion cueing results*

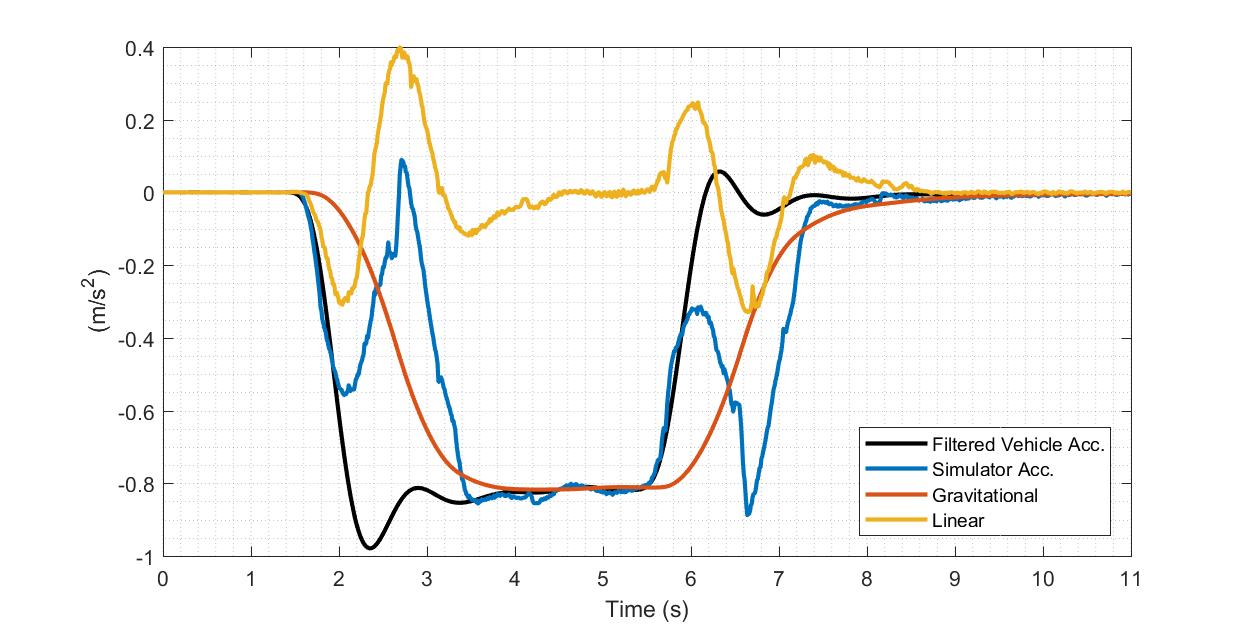
For the considered study, it is relevant to investigate how the complete motion cueing will perform in a braking maneuver. A typical braking signal applied by the simulator rider is sent to the vehicle model and the resulting longitudinal acceleration is computed by the Vehicle block. The vehicle acceleration signal is too noisy and needs to be filtered. Before being passed to the Map In block, the resulting acceleration was filtered with a Butterworth low pass filter of the fifth-order at 1 Hz. The normalized braking command between 0 and 1, the vehicle longitudinal acceleration and the filtered acceleration are shown in Figure S2. Between 1.2 and 5.2 seconds, the braking input from the rider generates a negative longitudinal acceleration that slows down the vehicle, which before 1.2 seconds is moving at 50 km/h. After the second 5.2 the vehicle reached a full stop and the acceleration goes to zero.



*Figure S2*. Effect of rider’s braking action on the longitudinal dynamics of the motorcycle. The vehicle acceleration signal is filtered before to be sent to the Map In block of the motion cueing algorithm.

The filtered vehicle acceleration is the output of the Vehicle block of Figure S1 and it is then passed to the remaining blocks of the adaptive motion cueing algorithm, which compute the reference positions and orientations for the motion system. The actual motion of the system is logged during the maneuver with the motion system control software interface, and the resulting positions, velocities, and accelerations in all degrees of freedom are extracted. The actual acceleration given by the motion system is compared with the reference vehicle acceleration in Figure S3. The reference vehicle acceleration shown in Figure S3 differs from the one shown in Figure S2 only by the scale factor of 0.25 for the longitudinal acceleration and reported in Table S1.

In order to reproduce the reference acceleration, the platform combines linear and rotational motion. The linear motion is used to provide the high-frequency content of the acceleration, while the rotational motion is used to tilt the motion platform and use a component of the gravitational acceleration to reproduce sustained acceleration. Both contributions are represented in Figure S3. The resulting acceleration provided by the motion system resembles the reference acceleration, with visible differences in the acceleration shape in the beginning and at the end of the maneuver.

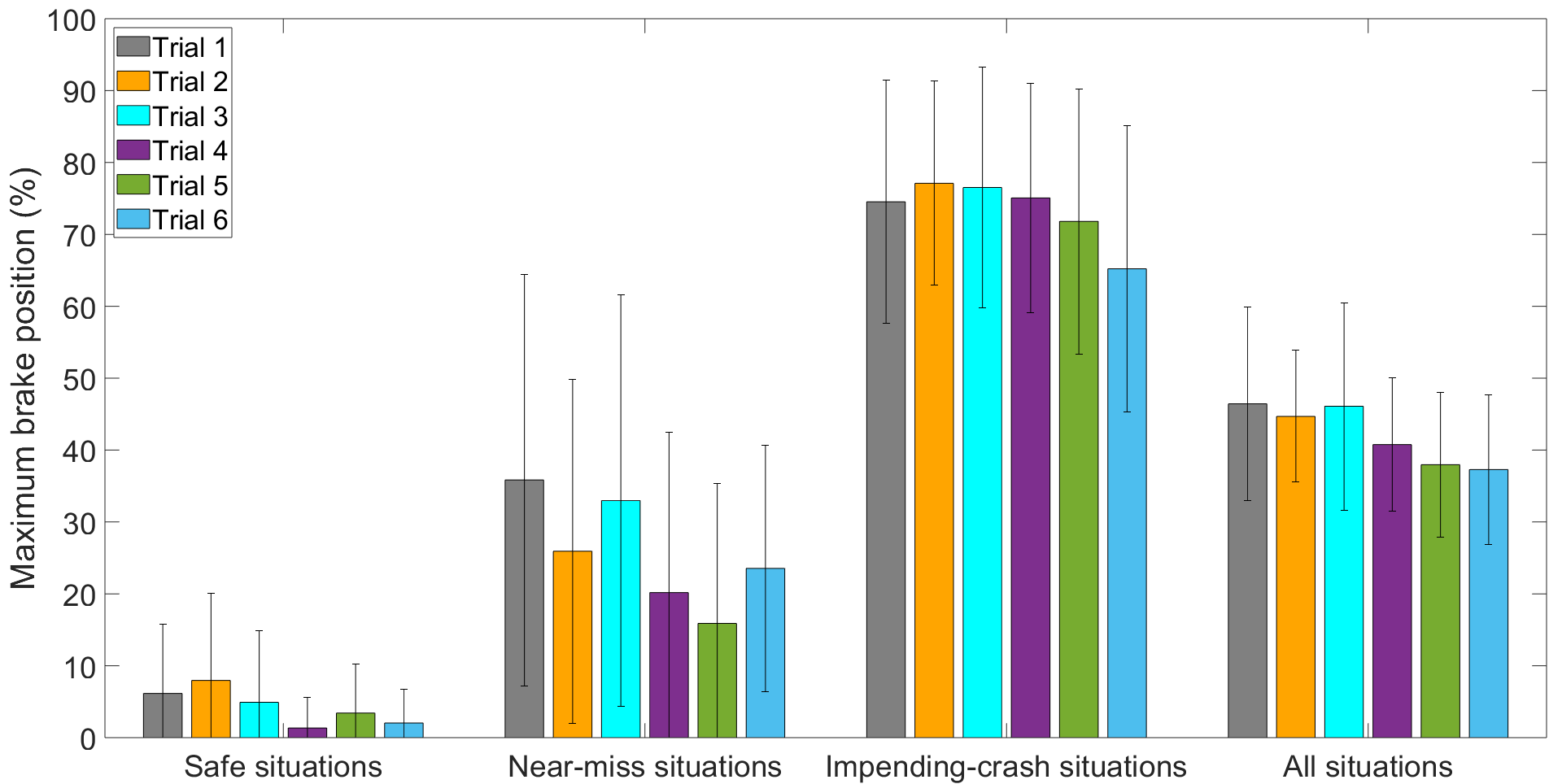


*Figure S3.* Comparison between the reference vehicle acceleration and the acceleration reproduced by the simulator for the longitudinal acceleration during the braking maneuver. The acceleration given by the simulator is the combined effect of linear acceleration and rotational motion, where the motion system rotation allows to use the gravitational acceleration to reproduce sustained acceleration.

Abbreviations

|  |  |
| --- | --- |
| Acc. | Acceleration: first order time derivative of the velocity |
| CG | Center of gravity of the vehicle |
| CRP | Reference frame of the vehicle rider’s head |
| FPC | Center of the fixed based of the simulator |
| HP | High-Pass |
| LP | Low-Pass |
| MPC | Center of the moving base of the simulator |
| Pos. | Position |
| RRP | Reference frame of the simulator rider’s head |
| Rx, Ry, Rz | Rotational motion along X, Y and Z directions |
| Tx, Ty, Tz | Translational motion along X, Y and Z directions |
| Vel. | Velocity: first order time derivative of the position |

**Learning curves**

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*Figure S4.* Mean ± Standard deviation of participants for the maximum brake position for trials 1 to 6. A distinction is made between the two safe situations, the three near-miss situations, and the four impending-crash situations, and all nine situations combined.