Simulating the effects of a virtual motorcycle passenger on vehicle motion and rider effort

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Motivation

Motorcycles and other single-track vehicles are popular but dangerous methods of transportation. While much of this risk comes from motorcycles' interaction with other traffic, some is because motorcycles are only open-loop stable at certain forward velocities. Even with a skilled rider, driving over uneven road surfaces, such as curbs and rutted pavement can excite dynamics that are difficult to control. In addition, motorcycles are not only ridden by drivers, but also by passengers. Since motorcycle passengers may have either adverse or helpful effects on human-ridden motorcycle dynamics, evaluating how an artificial, virtual passenger might change the closed-loop dynamics of a self-driving motorcycle could help build better test vehicles for all of the use cases summarized above.

The motorcycle passenger model

Unlike the motorcycle's rider, a passenger can only perceive rear frame motion, and can only affect vehicle stability through torso lean.

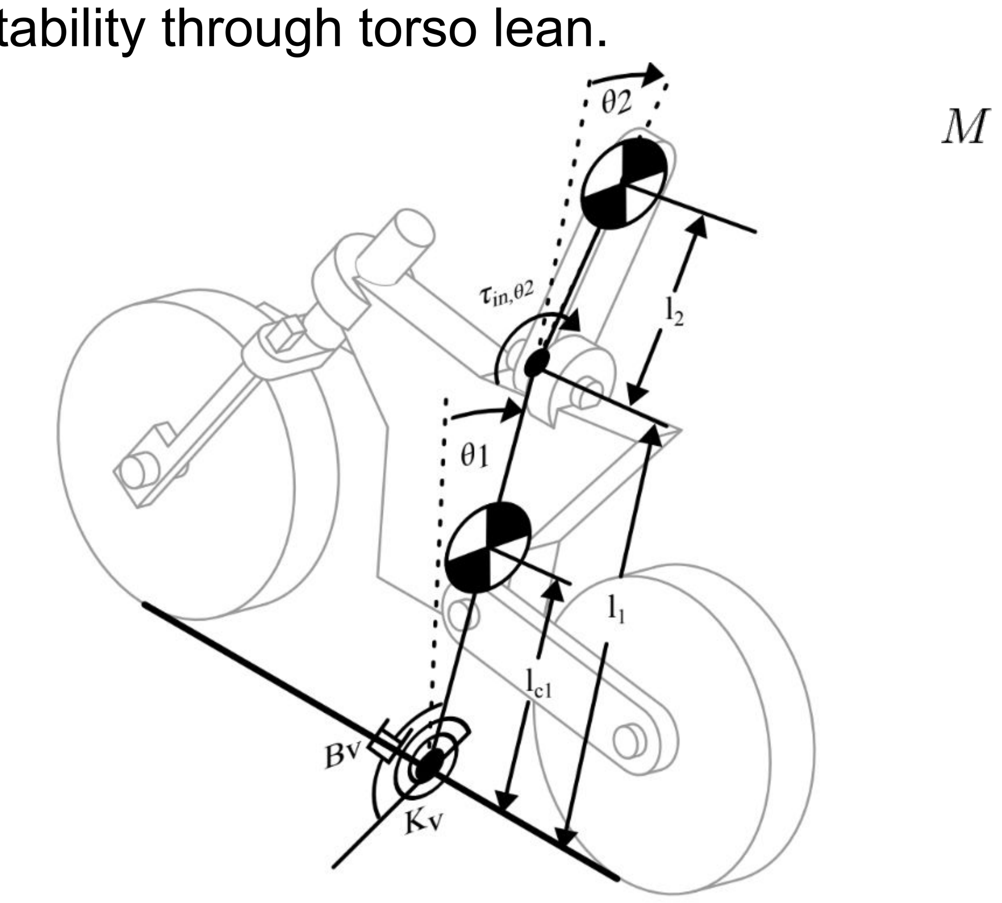


Fig. 1: Model of the rider-vehicle -passenger system with an active passenger. Based on the Acrobot[1] model with the addition of a "virtual spring" and "virtual damper" at the ground hinge to represent the rider's stabilization efforts through steering.

Modified Spring-Mass-Damper Form:

$$M\ddot{\vec{q}} + D\dot{\vec{q}} + K\vec{q} = F\vec{u} \quad \text{with} \quad \vec{q} = \begin{bmatrix}\theta_1 & \theta_2\end{bmatrix}^\intercal$$

$$M = \begin{bmatrix} m_1 l_{c1}^2 + m_2 l_1^2 + m_2 l_{c2}^2 + 2m_2 l_1 l_{c2} + I_1 + I_2 & m_1 l_{c2}^2 + 2m_2 l_1 l_{c2} + I_2 \\ m_1 l_{c2}^2 + 2m_2 l_1 l_{c2} + I_2 & m_1 l_{c2}^2 + I_2 \end{bmatrix}$$

$$D = \begin{bmatrix} B_v & 0 \\ 0 & 0 \end{bmatrix}$$

$$K = \begin{bmatrix} K_v - m_1 l_{c1} g - m_2 l_1 g - m_2 l_{c2} g & -m_2 l_{c2} g \\ -m_2 l_{c2} g & -m_2 l_{c2} g \end{bmatrix}$$

State-Space Form:

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \quad \text{with} \quad \vec{x} = \begin{bmatrix}\vec{q} & \dot{\vec{q}}\end{bmatrix}^\intercal$$

$$\underbrace{\frac{d}{dt}\begin{bmatrix}\theta_1 \\ \theta_2 \\ \dot{\theta}_1 \\ \dot{\theta}_2\end{bmatrix}}_{\dot{\vec{x}}} = \underbrace{\begin{bmatrix} 0_{2\times2} & I_{2\times2} \\ -M^{-1}K & -M^{-1}D \end{bmatrix}}_{A} \underbrace{\begin{bmatrix}\theta_1 \\ \theta_2 \\ \dot{\theta}_1 \\ \dot{\theta}_2\end{bmatrix}}_{\vec{x}} + \underbrace{\begin{bmatrix} 0_{2\times2} \\ M^{-1}F \end{bmatrix}}_{B} \underbrace{\begin{bmatrix}\tau_{in,\theta_1} \\ \tau_{in,\theta_2}\end{bmatrix}}_{\vec{u}}$$

The passenger's attempt to balance through torso motion is represented by an LQR controller with torque acting on θ_2, $Q = I_{4\times4}$, and $R = 1000$.

The passenger's internal model of rider action

The "virtual spring" K_v and "virtual damper" B_v at the ground hinge, modeling rider steering stabilization, were found by fitting a second-order model to the vehicle's closed-loop behavior while the passenger's torso was "locked" in place. Actual rider steering action was achieved using an LQR based on a 4th order model of vehicle dynamics.

$$T_d = \left(m_1 l_{c1}^2 + m_2 (l_{c1} + l_2)^2 + I_1 + I_2\right)\ddot{\theta}_1 + B_v\dot{\theta}_1 + \left(K_v - (m_1 + m_2)(l_1 + l_2)\, g\right)\theta_1]$$

T_d is a fictitious disturbance torque, while K_v and B_v represent stabilization efforts by the rider.

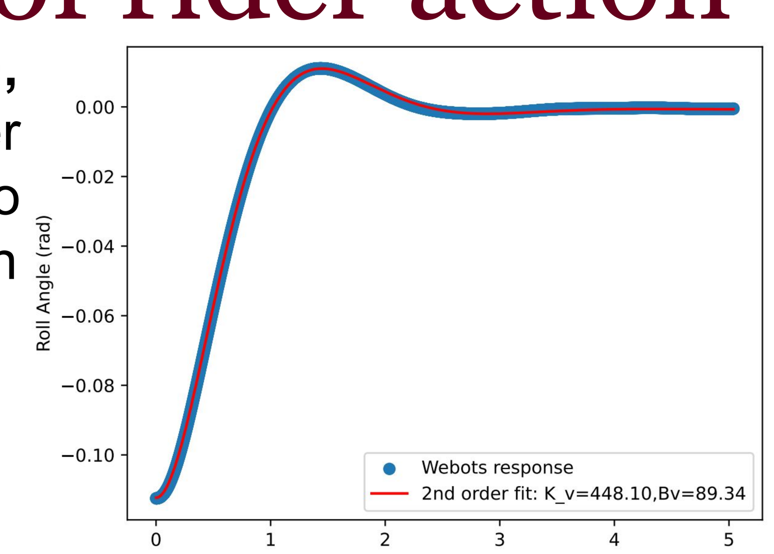
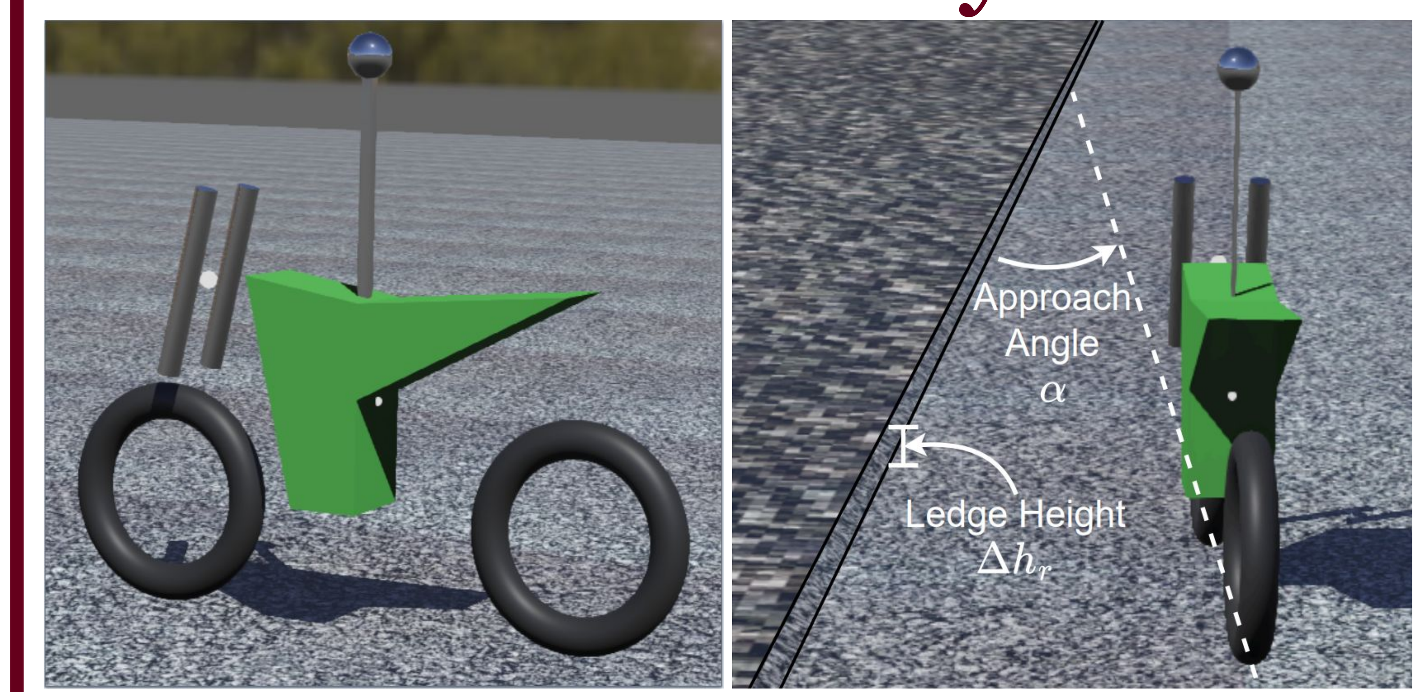


Fig. 2: 2nd order model fit compared to Webots response

References: [1] M. Spong, "The swing up control problem for the Acrobot," IEEE Control Systems Magazine, vol. 15, no. 1, pp. 49–55, Feb. 1995, conference Name: IEEE Control Systems Magazine. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/341864 [2] W. Li, P. Francis, R. McClosky, and A. Brown, "Webikes: a configurable, open-source add-on for simulating single-track vehicle dynamics in the webots robot simulation software," Advances in Transportation Studies, vol. Special Vol. 4, pp. 73–88, 2024.

Simulations of dynamics over uneven terrain



- Goal $\theta_1 = 0$ for all simulations
- $U = 11.2$ m/s for all simulations
- $\Delta h_r = [0.125'', 3'']$ in $0.125''$ increments
- $\alpha = [2^\circ, 20^\circ]$ in 1° increments
- Analyzed θ_1 and T_δ for each setup

Fig. 3: Webots representation of motorcycle[2] with active passenger (left). Annotated simulation environment highlighting approach angle α and ledge height Δh_r (right).

Comparing "rigid" vs. "active" passengers

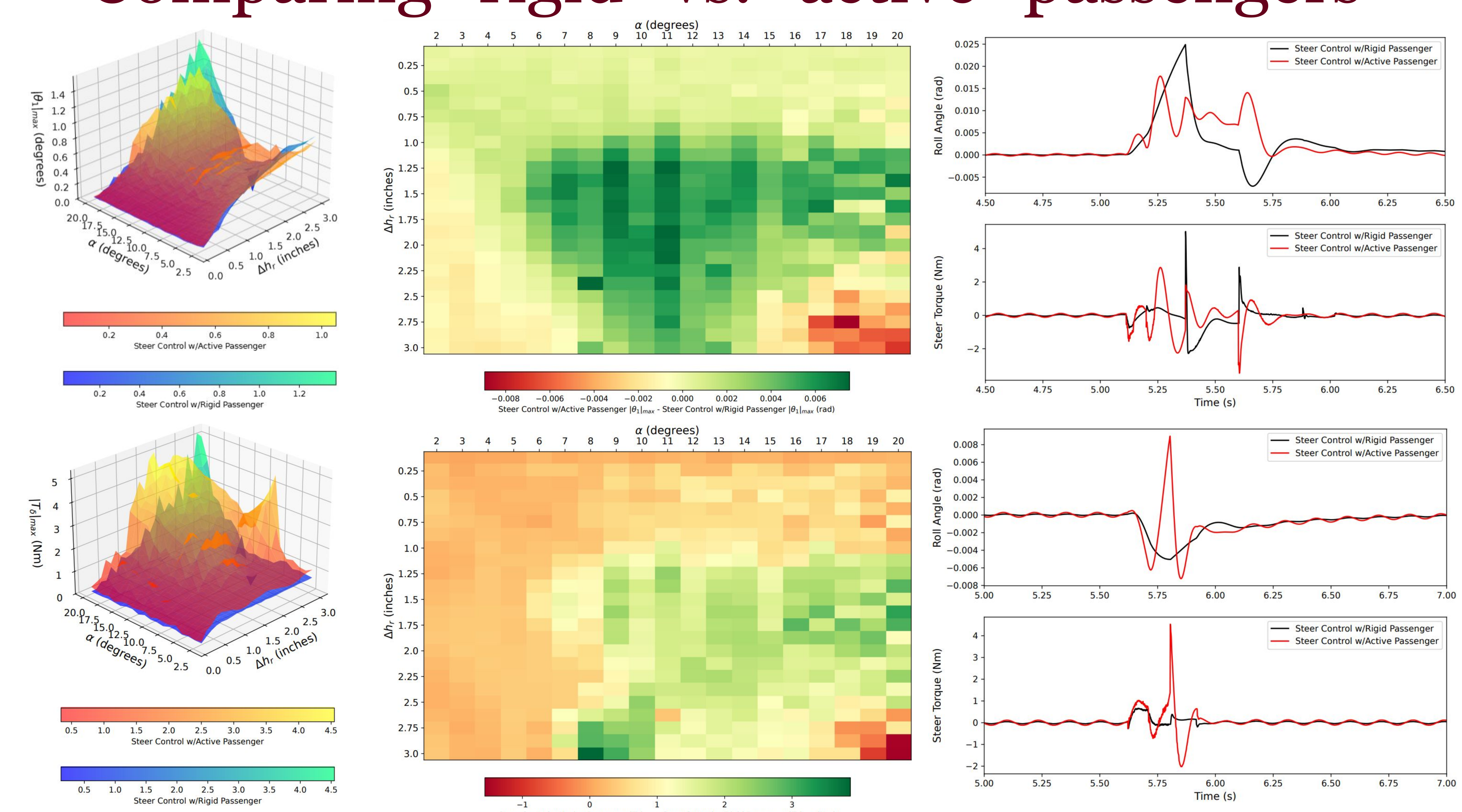


Fig. 4: Maximum roll angle (top left) and maximum rider steer torque (bottom left) for system with rigid and active passenger over each height transition. Difference between maximum roll angles (top middle) and maximum steer torque (bottom middle) for each environment configuration. Time-series plots of vehicle roll angle and rider steer torque for a ledge height of 3 inches and an approach angle of 20 degrees (top right) and for a ledge height of 3 inches and an approach angle of 8 degrees (bottom right).

Considering passenger motion is *safety critical*

These results show that the passenger's control efforts have mixed effects on both rider effort and vehicle stability over abrupt transitions in pavement height. However, it is clear that the inclusion of passenger motion is critical when vetting the safety of roadway designs and/or emerging motorcycle safety technologies like Advanced Rider Assist Systems.