A Comparative Study of Discomfort Using Electrical and Friction Braking at Low Speed Driving

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Abstract. In this study, we conduct an analysis of the longitudinal dynamics of a vehicle model in an incline, with a specific focus on its behavior, at low speeds, when starting and stopping. The model is minimal, yet an effective representation of a vehicle that includes the effects of springs and dampers as well as friction and electric braking models, which allows for easy analysis into their interplay at low speed. One important feature that this early study shows is how the acceleration and jerk is affected by static and dynamic friction coefficients in different driving situations. Our study further demonstrates the interplay between the electric and friction braking systems and the differences in oscillatory motion they generate. Such insights are vital if we want to improve vehicle control at low speeds and suggest ways to reduce problems like excessive acceleration and jerk. Additionally, our findings could also provide valuable insights when developing active friction braking systems.

Keywords: Longitudinal dynamic · Standstill · Braking system

1 Introduction

1.1 Background and Literature Review

Most everyday driving involves non-extreme maneuvers, nevertheless, ride comfort is often compromised by frequent starts and stops. Ride discomfort is caused by acceleration and jerk (the rate of change in acceleration). As the vehicle accelerates, passengers experience inertia forces, leading to discomfort when these forces are large or change rapidly. Additionally, both uphill and downhill driving affect comfort by shifting weight distribution between the two axles, which in turn influences the potential for regenerative braking power. Specifically, in downhill driving, Chen *et al.* [1] investigate a regenerative braking strategy for electric vehicles on varied slopes. They analyzed the effect of the slope on braking, and introduced an online co-estimation of road slope and vehicle mass using neural networks and a least-squares algorithm.

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Many studies have been done on longitudinal ride comfort. Hou *et al.* [2] present a novel control strategy using residual reinforcement learning to enhance vehicle ride comfort during the post-braking phase in urban environments. Experimental tests on a skateboard chassis confirm its effectiveness in improving comfort across different braking scenarios. The relationship between acceleration, jerk, and passenger discomfort was examined in [3], using a driving simulator with 23 participants. That test showed that discomfort increases with acceleration amplitude, and that the strength of this effect depends on the direction of motion. Lee and Choi [4] focused on enhancing ride comfort in low-risk braking situations. Their research was conducted on Electro-Mechanical-Brake (EMB) and Brake-by-Wire (BBW) systems, which allow for more precise control of braking actuators. A control algorithm was developed that significantly improved ride comfort by generating an acceleration trajectory designed to minimize discomfort caused by sudden changes in acceleration and jerk. A key aspect of this improvement is the reduction of jerk, ensuring smoother transitions and a more comfortable driving experience. In order to control and minimize jerk, Singh *et al.* [5] introduced an autonomous emergency braking system. The system's stopping distance was analytically calculated, and a simple controller tracked the desired velocity profile. In [6], a novel braking method using an integrated electro-hydraulic brake system was proposed to improve ride comfort. The proposed method comprises target acceleration generation, revision of target acceleration, and acceleration tracking control. The tracking control included both feedforward and feedback control, which were used to precisely track the target acceleration.

1.2 Motivation

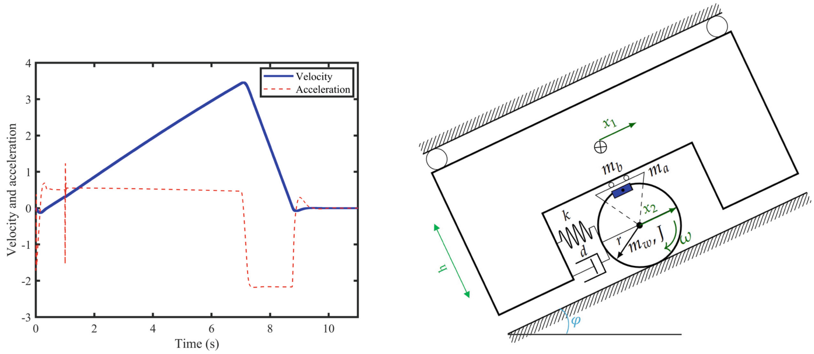
In this study, we investigate and analyze the behavior of vehicle motion at low-speeds using a minimal vehicle model that captures the main longitudinal dynamics phenomena. Our research specifically focuses on scenarios of starting and stopping in an uphill, where both propulsion and friction braking torques are engaged. We do this by testing how the relation between static and dynamic friction coefficients affect the dynamics. We then study acceleration and jerk under different conditions to understand the conceptual comfort difference between using a shaft torque, generated from for example an electrical motor, and a friction brake force. By gaining a deeper understanding of vehicle dynamics in this particular scenario, we seek to pave the way for further understanding of how to reduce excessive jerk when starting and stopping, and thus provide solutions for better ride comfort in everyday driving conditions.

2 Modelling

2.1 Model Description

For the current study, we have developed a minimal vehicle model to capture a few aspects of longitudinal comfort at low speed, which is shown in Fig. 1(b). The model includes a vehicle body, a wheel hub and wheel. The body is supported by a spring-mass suspension system that is attached to a wheel hub.

The vehicle body has a sprung mass m_b, the wheel hub has mass m_a and the wheel has mass m_w, radius r, and moment of inertia J. Further, the suspension system comprises a spring and damper, with parameters k and d, respectively, which allow the wheel to have a translational motion in relation to the vehicle body. We let x_1 and x_2, respectively, be the vehicle's body and wheel displacement relative to the surface, $\dot{x}_1$ and $\dot{x}_2$ their respective velocities, and $\dot{x}_1$ and $\dot{x}_2$ their accelerations. The angular velocity of the wheel is ω, the propulsion torque acting on the wheel is T_p, and the clamp force of the break is F_c. We finally assume that here is no slip between the tyre and ground, and thus $\dot{x}_2 - r\omega = 0$.



(a) (b)

Fig. 1. (a) Vehicle velocity and acceleration from Carmaker, (b) The minimal vehicle model.

We note that the model simplifies a vehicle's complexity by lumping all wheels into a single representative wheel. Here we considered wheel as a solid model and the stiffness and damping characteristics from the tires and suspension are consolidated into a spring and damper setup. The model has two degrees of freedom, which are the movement of the sprung mass and the wheel. The effects of motion resistance such as air drag, rolling, etc. are omitted.

Taking all this into consideration, the equations of motion for the system on a road with an inclination angle φ are given by

$$m_b\ddot{x}_1 - k(x_2 - x_1) - d(\dot{x}_2 - \dot{x}_1) = m_b g \sin(\varphi), \tag{1}$$

$$\frac{J + r^2 m_s}{r}\ddot{x}_2 + rk(x_2 - x_1) + rd(\dot{x}_2 - \dot{x}_1) = T_p(t) - rF_b(\dot{x}_2) + rm_s g \sin(\varphi), \tag{2}$$

where $m_s = m_a + m_w$ and the friction force F_b is given by

$$F_b(\dot{x}_2) = \begin{cases} [-\mu_s F_c, \mu_s F_c], & \dot{x}_2 = 0, \\ -\left(\mu_d + (\mu_s - \mu_d) \cdot \exp\left(-\left(\frac{\dot{x}_2}{v_s}\right)^\alpha\right)\right) \mathrm{sign}(\dot{x}_2/r) \cdot F_c, & \dot{x}_2 \neq 0. \end{cases} \quad (3)$$

and includes the Stribeck effect (with Stribeck velocity v_s), and static and dynamic friction coefficients μ_s and μ_d, respectively.

2.2 Parameter Selection

The lumped parameters of the model were selected through a comparative analysis between our proposed model and a standard model provided by the simulation tool Carmaker. This comparison was conducted to ensure that both models exhibited similar natural frequencies. Results from Carmaker (for an example see Fig. 1(a)) were used to adjust the parameters until the frequency response of the minimal model matched that of the Carmaker model. This process helped in ensuring that the simplified model well represents the dynamics of a Carmaker vehicle model.

3 Simulation

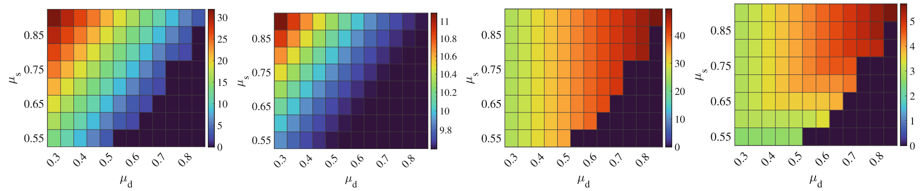
3.1 Driving Scenario

Simulations and solving the equations of motion were done using MATLAB & Simulink. The two scenarios we analysed were starting and stopping in a hill. During all simulations the propulsion torque $T_p(t)$ varies, while the clamp force F_c remains constant, ensuring that there is always a sufficient friction braking torque to bring the model to a complete stop.

3.2 Results

By analyzing the jerk of the main body, some levels of rapid changes are observed when the wheel starts moving and when it comes to a complete stop. To analyze role the friction in the brake has in these scenarios, the body acceleration and jerk were calculated for different static and dynamic friction coefficients, as shown in Fig. 2. In order to minimize noise when calculating signal derivatives, such as jerk, and to ensure accurate analysis and detection, we employ a 6 Hz low-pass filter [7]. This significantly reduced noise and minimized fluctuations in the derivatives, which enhanced the clarity and reliability of the results for analysis.

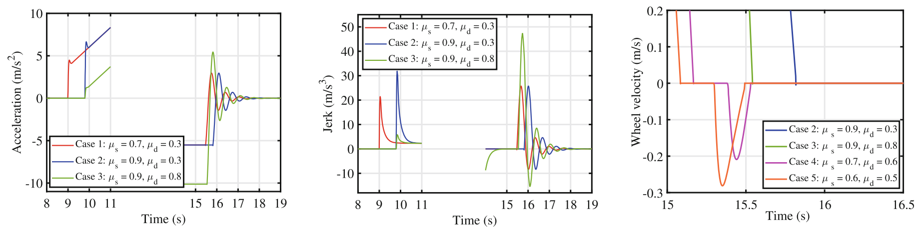
As can be seen in Fig. 2(a) and 2(b), jerk and acceleration of the body increases significantly with higher static friction coefficients μ_s and lower dynamic friction coefficients μ_d, when the vehicle starts moving. Here the friction brake must transition from a static to a dynamic state, which means that when the static friction coefficient is big, the maximum static friction force will be greater and requires more force to overcome in order to initiate motion. A



(a) (b) (c) (d)

Fig. 2. The maximum body (a) jerk and (b) acceleration during start, an maximum (c) jerk and (d) acceleration during stop are shown for μ_s and μ_d.

consequence is that this results in greater jerk. Conversely, a small μ_s and a large μ_d lead to smoother transitions and reduced jerk. This indicates that very high μ_s and very low μ_d gives discomfort in start scenarios on uphill. Instead, when stopping, Fig. 2(c) and (d) show the jerk and body acceleration after the wheel has stopped rotating. As seen in the figures, μ_s seems to have a small effect when stopping while μ_d plays an important roll. An increase in μ_d increase both jerk and acceleration, but they are both almost constant for a given μ_d and varying μ_s. To observe the effects the difference $\Delta\mu = \mu_s - \mu_d$ between the two coefficients have, we chose three different cases to analyze. The body acceleration and jerk for these cases are shown in Fig. 3.



(a) (b) (c)

Fig. 3. Time histories for (a) body acceleration, (b) body jerk and (c) wheel speed.

As can be seen in Fig. 3(a), when the model starts moving, we see for all three cases that there is a jump in acceleration, resulting in a large jerk (see corresponding plot in Fig. 3(b)). In particular, jerk is largest for Case 2, with the largest $\Delta\mu$, and the smallest for Case 3, with the smallest $\Delta\mu$. However, when stopping, Case 3 has the largest jerk. It can also be seen that the three cases have similar oscillations when stopping, and for Cases 1 and 2 the maximum jerk and acceleration is the same since they have the same μ_d. From Fig. 2 we know that a change in μ_s only has a small effect on the jerk, when stopping. In general, μ_s has no effect when stopping, but when μ_s is small and close to μ_d, the wheel may start rotating again, thereby affecting and reducing acceleration. Cases 4 and 5 in Fig. 3(c) demonstrate this behavior.

4 Conclusion

In the present study, we introduce a minimal longitudinal model that incorporates the effects of springs and dampers as well as friction and electric braking. We examined the behavior of the vehicle at low speeds when starting and stopping in an uphill when varying the friction coefficients of the friction break. The results indicate that μ_d and μ_s have different impact depending on the scenario. The combination of a small value for μ_d and a large value for μ_s increases discomfort when starting. Conversely, a large μ_d, independent of μ_s, when stopping also increases discomfort. Additionally, as the difference $\Delta\mu$ between the friction coefficients decreases, increased oscillations are experienced when stopping. This study can be used to enhance the understanding of the interplay between friction and electric brake close to zero speed, and thus help us improve comfort by reducing jerk. In future research, we can utilize this model to develop a controller for managing jerk more effectively as well as including a more realistic tire model and enhance the current friction model, and thereby improving both performance and validity in special scenarios.

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