Measurement Framework for Quantifying Braking Comfort in Automated Vehicles

Wenqi Wendy Guo, Zeid Kootbally, Thomas P. Roth
National Institute of Standards and Technology (NIST)
Gaithersburg, MD, USA
{wenqi.guo, zeid.kootbally, thomas.roth}@nist.gov

Ninad Harishchandrakar
PREP Associate, NIST
Gaithersburg, MD, USA

University of Maryland
College Park, MD, USA

Sanchit S. Kedia
Pyka Inc.
Alameda, CA, USA

***Abstract*—Passenger comfort is an essential component of automated vehicle acceptance, yet braking comfort remains difficult to quantify using objective and reproducible measurements. This work develops a measurement framework for characterizing braking comfort through controlled vehicle experiments and synchronized analysis of driver reaction time, longitudinal acceleration, jerk, and braking duration. A comprehensive dataset was collected using an instrumented automated vehicle across a range of stopping distances and speeds representative of urban and highway driving conditions. Experimental results reveal that braking behavior is primarily governed by the available stopping distance, with shorter distances producing higher deceleration, larger jerk transients, and reduced braking duration. These observations establish a distance-constrained braking regime that directly links information availability to achievable braking smoothness. The collected data provide a realistic foundation for simulation and modeling of braking behavior and enable future evaluation of communication-assisted driving strategies. In particular, Vehicle-to-Infrastructure (V2I) and Vehicle-to-Network (V2N) communication can extend effective stopping distance by providing earlier awareness of traffic signals, hazards, and roadside conditions, thereby enabling smoother braking maneuvers. The proposed framework establishes a standardized measurement baseline for assessing the impact of connected vehicle technologies on passenger comfort.**

***Index Terms*—Automated vehicles (AV), braking comfort, V2X, jerk, acceleration**

I. Introduction

Automated vehicles (AVs) are expected to improve safety and efficiency in future transportation systems; however, passenger comfort remains a critical factor for user acceptance. Among various driving behaviors, braking has a dominant influence on ride quality, as high deceleration and abrupt motion changes can lead to discomfort and motion sickness [1]. This challenge is particularly pronounced in automated driving, where passengers lack anticipatory control and are more sensitive to unexpected vehicle dynamics.

Passenger comfort is inherently subjective, but for system design and evaluation, it must be assessed through objective and reproducible measurements. Prior work has identified longitudinal acceleration and jerk as key indicators of discomfort [2], and standards such as International Organization for Standardization (ISO) 2631-1 [3] provide a foundation for evaluating human exposure to motion. In automated driving research, these metrics are often incorporated into control frameworks to constrain vehicle motion [4]–[6]. There is limited emphasis on standardized measurement methodologies that ensure reproducibility and enable consistent comparison across experimental conditions. Braking behavior is fundamentally governed by the available stopping distance and the initial vehicle speed. When the available distance is limited, higher deceleration and jerk are required to achieve a full stop, leading to reduced passenger comfort [7], [8]. Despite its importance, stopping distance has not been systematically characterized as a governing variable in experimental studies of braking comfort.

To address these challenges, this paper presents a measurement-driven framework for quantifying braking comfort in automated vehicles. A controlled experimental methodology is developed using an instrumented vehicle platform and a structured distance–speed test configuration, enabling systematic data collection under repeatable conditions. A signal-based event definition ensures consistent alignment of braking onset across trials, and all measurements are represented in a unified distance-based framework to facilitate direct comparison across scenarios. The contributions of this work are threefold. First, we establish a reproducible experimental framework for measuring braking behavior using synchronized vehicle telemetry and standardized data processing. Second, we demonstrate that braking dynamics follow a distance-constrained regime, where stopping distance governs both acceleration magnitude and motion smoothness. Third, we provide a quantitative foundation for evaluating communication-assisted braking, where Vehicle-to-Infrastructure (V2I) and

Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

This manuscript was edited with the assistance of a grammar tool. It was used to refine language, improve clarity, and enhance readability in accordance with the authors' instructions. All content, scientific claims, and conclusions have been reviewed and verified by the authors to ensure accuracy and originality.

S. S. Kedia was with the National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA, when this work was performed. He is now with Pyka Inc., 950 W. Tower Ave., Alameda, CA, USA.

Vehicle-to-Network (V2N) communication can extend effective stopping distance and improve passenger comfort.

II. Experimental Methodology

This section describes the AV test platform, experimental design, and data acquisition process used to evaluate braking behavior under controlled conditions. The methodology is designed to ensure repeatability, precise alignment of braking events, and consistent comparison across trials.

A. Test Platform and Instrumentation

Experiments were conducted using a modified Ford Fusion Hybrid automated vehicle serving as the NIST Automated Vehicle Testbed (NAVT), as shown in Fig. 1. The platform is equipped with a drive-by-wire interface, enabling precise longitudinal motion control and direct access to vehicle control signals. Accurate vehicle localization and motion estimation are achieved using a tightly coupled Global Navigation Satellite System (GNSS) and Inertial Navigation System (INS). The GNSS/INS system operates at high sampling rates, enabling precise reconstruction of vehicle trajectories and motion states. This integration supports accurate estimation of remaining stopping distance and alignment of braking events.

Fig. 1. NIST Automated Vehicle Testbed

A high-performance onboard computing unit running Ubuntu 22.04 and Robot Operating System 2 (ROS 2) [9] manages sensor synchronization, data logging, and control communication, as shown in Fig. 2. All vehicle telemetry, including speed, position, acceleration, and brake torque request, is recorded in synchronized ROS 2 bag files, ensuring consistent temporal alignment across all signals for post-processing and analysis.

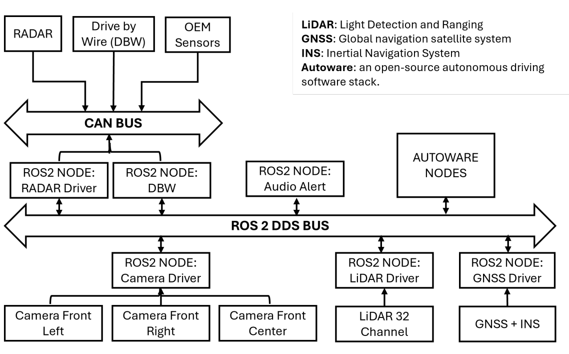

Fig. 2. NAVT ROS 2 system architecture

B. Experimental Design

The experiment follows a controlled braking scenario in which the driver brings the vehicle to a predefined speed and maintains it using adaptive cruise control (ACC) prior to a designated braking location. As the vehicle approaches this location, an auditory cue is played, and the driver is instructed to press the brake pedal immediately after the cue ends to initiate braking. A structured set of stopping distances ranging from 10 m to 150 m is evaluated in combination with multiple approach speeds that span typical urban to highway conditions (6.7–26.8 m/s), allowing the generation of braking profiles over a wide range of deceleration demands. To ensure consistency across trials, braking onset is defined using a signal-based trigger associated with the auditory cue. Specifically, the start of braking is identified as the moment immediately following the end of the audio signal when the driver starts to step on the brake pedal. This approach provides a repeatable reference point for aligning time-series data across experiments and enables measurement of driver reaction time as a baseline for comparison with future communication-assisted V2I scenarios.

1) Distances and Speed: To ensure consistent initial conditions, the driver uses ACC to maintain the target speed prior to the braking point. Before each trial, the driver accelerates to the target speed and engages cruise control before the braking initiation point. The driver is then only responsible for executing the braking action, isolating braking behavior from variability in speed control. Each distance–speed condition is repeated multiple times to ensure statistical consistency and to account for variability in driver response.

2) Braking Event Definition: A signal-based approach is used to standardize braking initiation across trials. An auditory cue is generated prior to the braking point, with a fixed lead time relative to the vehicle's current speed. The trigger distance is computed as in Eq. (1),

$$d_{\text{alarm}} = v \cdot t_{\text{lead}} \tag{1}$$

where v is the vehicle speed and $t_{\text{lead}} \approx 3$ s is the duration of the audio cue.

The driver is instructed to initiate braking immediately after the audio cue ends. Braking onset is detected using the `brake_torque_request` signal, with a predefined threshold applied to distinguish intentional braking from noise.

3) Driver Reaction Time: Driver reaction time is measured as a baseline reference, since perception–reaction time directly determines the portion of stopping distance consumed prior to braking [13]. Thus, reducing this delay through communication-based automated driving systems (ADS) can effectively extend the available stopping distance, directly influencing braking smoothness and passenger comfort. Driver reaction time is defined as in Eq. (2),

$$t_{\text{reaction}} = t_{\text{brake torque request}} - t_{\text{alarm end}} \tag{2}$$

where $t_{\text{brake torque request}}$ is the time at which braking is requested and $t_{\text{alarm end}}$ is the end time of the auditory cue. This event-based definition ensures consistent temporal alignment of braking trajectories across trials. Driver reaction time serves as a baseline metric for assessing how communication-assisted perception reduces response delay, extends effective stopping distance, and enables smoother braking.

An overview of the experiment implementation flowchart is shown in Fig. 3. Each trial follows a structured sequence consisting of system validation, cruise control stabilization, alarm triggering, braking execution, and post-run verification.

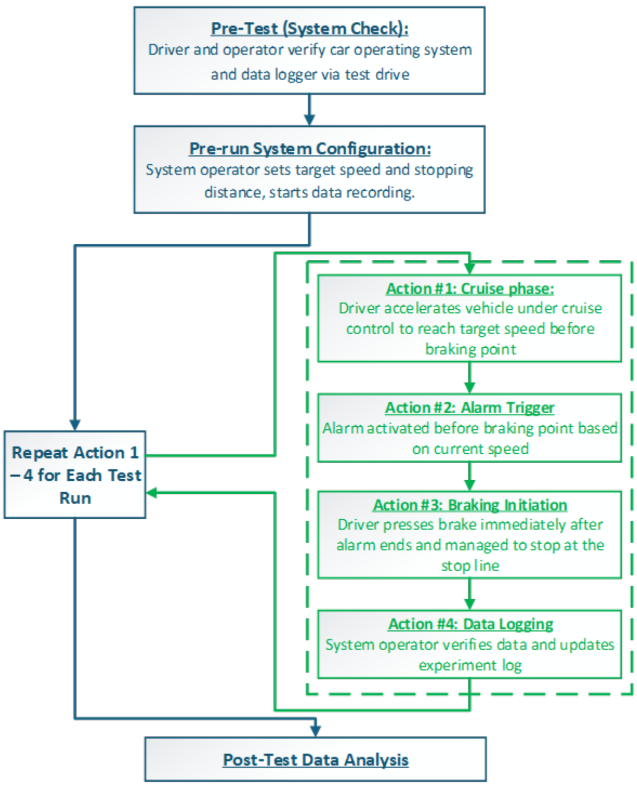

Fig. 3. Experiment implementation flowchart

This structured data collection and event-based alignment framework ensures repeatability and traceability of all experiments, enabling reproducible analysis of braking behavior as a function of initial speed and available stopping distance. More details about this framework are explained in [11].

C. Data Collection and Derived Metrics

All experiments are recorded using synchronized ROS 2 [9] bag files with a standardized naming convention that encodes stopping distance, speed, and trial index, enabling direct traceability to experimental conditions. All measurements are reported in International System of Units (SI) units to ensure consistency and comparability. All braking trajectories are aligned with respect to remaining stopping distance, computed using GNSS/INS-derived vehicle position relative to the predefined stop location. This distance-based representation enables consistent comparison of braking behavior across trials with different initial conditions.

From the processed signals, key braking metrics are derived as follows:

- **Driver reaction time**, as defined above.
- **Longitudinal acceleration**, representing braking intensity.
- **Jerk**, defined as the time derivative of acceleration.
- **Braking duration**, measured from braking onset to full stop.

III. Measurement Results and Discussion

This section presents experimental results obtained from the proposed measurement framework. Collected data during the experiments are published in [**?**]. The analysis focuses on how braking behavior varies as a function of remaining stopping distance and initial vehicle speed, and how these factors influence passenger comfort-related motion characteristics.

To address high-frequency noise introduced by oversampling in the raw acceleration data, we implemented a multi-step signal processing mechanism. First, we applied a Butterworth low-pass filter with a 5 Hz cutoff to suppress high-frequency components and minimize aliasing artifacts. This step ensured that the signal retained its essential dynamics prior to downsampling. Anti-aliasing filtering was followed by systematic downsampling to reduce data volume while preserving signal integrity. We further conducted frequency domain analysis using the Fast Fourier Transform to verify the presence of dominant frequency components. Additionally, Power Spectral Density estimation via Welch's method yielded a smoothed, robust frequency profile, confirming that the filtered and downsampled data accurately reflected the system's true physical behavior.

A. Driver Reaction Time as a Function of Speed

Across all evaluated scenarios, reaction time ranged from 0.01 s to approximately 0.18 s. Figure 4 presents driver reaction time as a function of vehicle speed, grouped by initial distance. The largest reaction times occur at lower speeds, while those at higher speeds are predominantly near zero. The negative slope of the regression trend indicates that driver braking initiation becomes increasingly synchronized with warning termination as vehicle speed increases. This pattern may reflect heightened perceived urgency at higher speeds, prompting faster braking response. Under elevated kinetic energy conditions, drivers may allocate attention more effectively and respond with reduced latency. The measured driver reaction times were consistent with values reported in prior human driving studies, which typically report braking reaction times less than 300 ms [12], [13], indicating that the experimental data captures representative driver behavior. The temporal characteristics of braking initiation identified in this subsection provide the foundation for the subsequent analysis of braking intensity and deceleration behavior.

B. Acceleration as a Function of Distance

Figure 5 illustrates the longitudinal acceleration profiles as a function of remaining stopping distance for multiple initial speeds and stopping distances. It indicates comfort levels [3], defined by the magnitude of longitudinal deceleration.

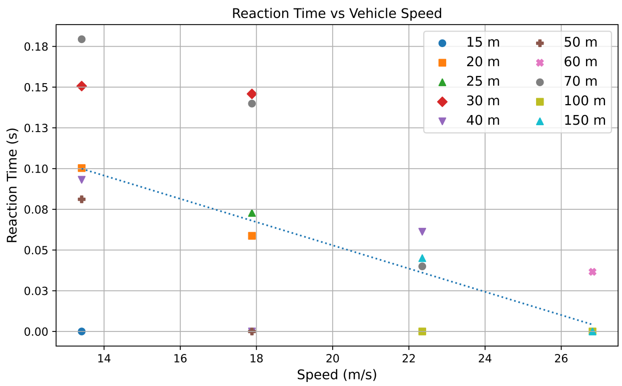

Fig. 4. Driver reaction time as a function of speed

It can be observed that trajectories associated with shorter stopping distances frequently enter the "uncomfortable" and "very uncomfortable" regions, particularly near the end of the braking maneuver. The results reveal a consistent trend in braking behavior across all test conditions: as the remaining distance decreases, the magnitude of deceleration increases progressively, with the most aggressive braking occurring in the final phase of the maneuver. For shorter initial stopping distances, the deceleration profiles exhibit a rapid increase in magnitude early in the braking process, followed by sustained high deceleration levels. This behavior highlights the strong dependency of braking intensity on the available stopping distance.

C. Jerk as a Function of Distance

The corresponding jerk profiles shown in Fig. 6 further reveal that braking includes pronounced transient responses. In particular, jerk spikes typically occur at the start of braking, marking the transition from cruising to deceleration and indicating the onset of braking. For a given initial speed, shorter stopping distances consistently produce larger jerk spikes, reflecting the need for more abrupt deceleration when the available distance is limited. This trend is consistently observed across all speed groups in the figure, where shorter stopping distances are associated with greater jerk variation. These transient effects are closely associated with increased passenger discomfort, even when the overall deceleration magnitude remains within acceptable limits.

D. Braking Duration

Table I presents braking duration as a function of stopping distance and initial speed, where the first column denotes stopping distance, the header row specifies initial speed, and each cell reports the measured braking duration for the corresponding condition. A consistent trend is observed: braking duration decreases as the available stopping distance is reduced. For example, at 11.18 m/s, the duration increases from 3.98 s at 40 m to 14.02 s at 150 m, indicating that shorter distances constrain the maneuver to a reduced time window. Across all shared distance conditions, higher initial speeds consistently result in shorter braking durations, indicating that increased deceleration demand leads to earlier and more aggressive braking, reducing the time required to complete the maneuver. This temporal compression aligns with the acceleration and jerk behaviors observed previously. Reduced braking duration requires the same speed reduction to occur over a shorter time, resulting in higher deceleration levels and sharper transitions, which correspond to increased acceleration magnitude and jerk in the final phase of braking. Together, these results show that stopping distance governs not only braking intensity and its rate of change, but also its temporal distribution. Limited distance compresses braking duration and leads to more aggressive motion profiles, while extended distance enables smoother deceleration with reduced transient effects.

TABLE I
MEASURED BRAKING DURATION (S) AS A FUNCTION OF DISTANCE AND VELOCITY

Stopping Distance (m)	Initial Velocity (m/s)			
	6.71	8.94	11.18	13.41
15	2.96	–	–	–
30	5.07	3.79	–	–
40	6.55	5.11	3.98	–
70	9.70	8.64	7.10	5.93
150	–	–	14.02	11.62

E. Key Observations and Implications

These results demonstrate that braking behavior is strongly governed by the available stopping distance. As the remaining distance approaches zero, braking becomes both more severe and less smooth, particularly at higher initial speeds. These results indicate that braking behavior follows a distance-constrained regime, where the available stopping distance is the main factor controlling both the magnitude and smoothness of vehicle motion. These findings are particularly relevant for evaluating communication-assisted scenarios, where extended stopping distance can be explicitly modeled and its impact on braking behavior quantitatively assessed.

IV. CONCLUSION AND FUTURE WORK

This paper presented a measurement-driven framework for evaluating braking comfort in automated vehicles using objective metrics derived from vehicle dynamics. By jointly analyzing longitudinal acceleration, jerk, and braking duration, the framework captures both sustained and transient braking characteristics in a consistent, reproducible manner. Experimental results demonstrate that braking behavior is governed by available stopping distance. Limited stopping distance results in higher acceleration magnitude, increased jerk, and shorter braking duration, whereas extended distance enables smoother, more gradual deceleration. These results establish stopping distance as the key factor determining braking smoothness and passenger comfort.

This observation provides a direct basis for evaluating communication-assisted driving. In traditional perception-based systems, braking is often initiated late due to sensing limitations, environmental occlusions, and driver reaction

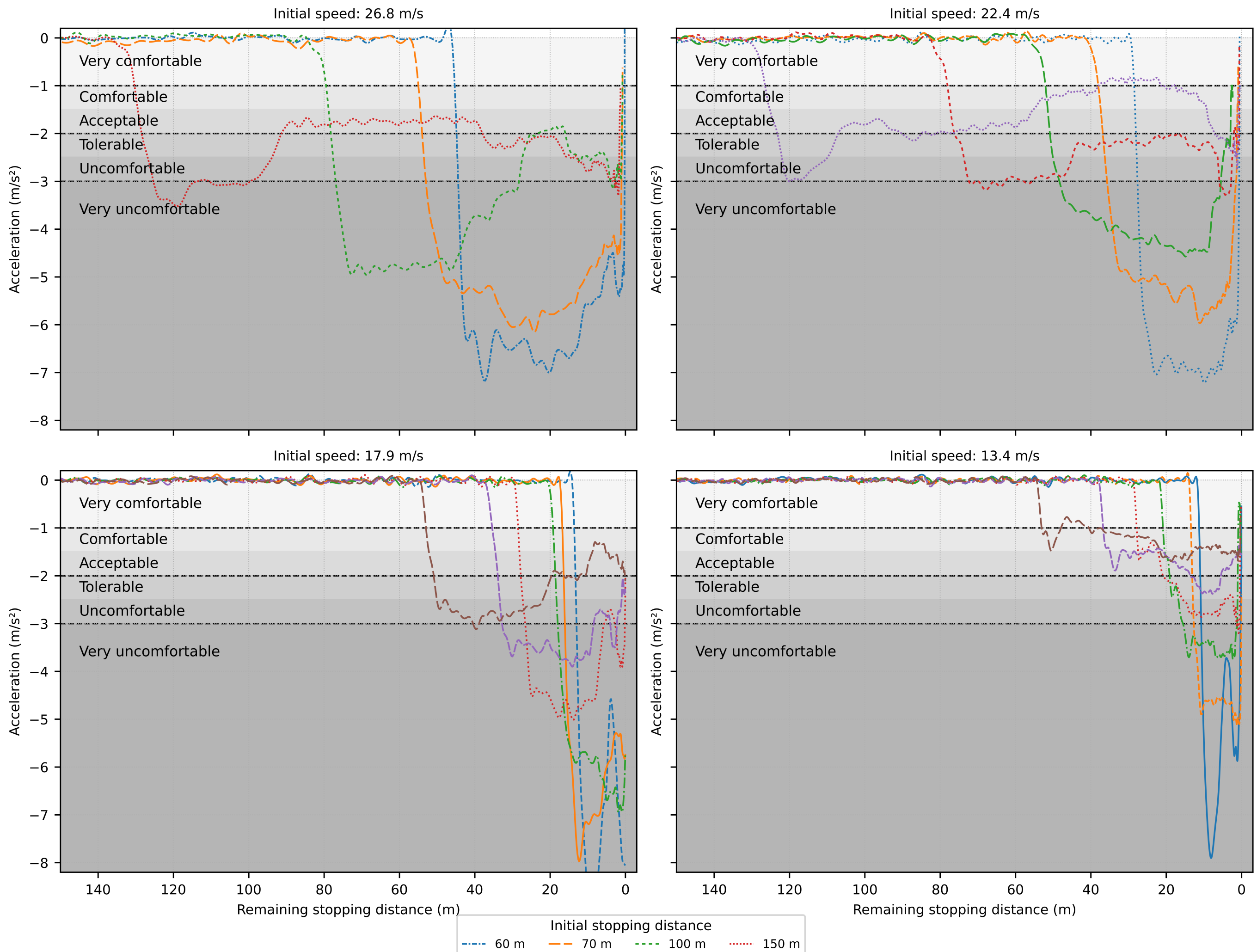

Fig. 5. Longitudinal acceleration profiles across stopping distances

time, leading to more aggressive maneuvers. Communication-assisted approaches, including V2I and V2N, extend situational awareness and enable earlier braking initiation. By effectively increasing the available stopping distance, these systems allow braking actions to be distributed over a longer distance, reducing acceleration magnitude and jerk while improving overall motion smoothness.

From an industry perspective, the proposed framework provides a practical and reproducible methodology for benchmarking braking comfort across vehicle platforms, control strategies, and connected driving functions. Because the framework relies on commonly available vehicle telemetry and objective performance metrics, it can be readily adopted by vehicle manufacturers, suppliers, and testing organizations to evaluate comfort-aware braking systems and quantify the benefits of communication-assisted driving technologies. The resulting dataset and analysis methodology also provide a valuable reference for the development, validation, and comparison of future automated driving systems.

Future work will integrate OBUs and RSUs to provide infrastructure-based information, such as Signal Phase and Timing (SPaT), hazard alerts, and speed constraints. In parallel, the collected dataset will be used to calibrate and tune simulation models, enabling controlled comparison between perception-only and communication-assisted scenarios while accurately representing real-world braking behavior. This will support systematic investigation of how communication-assisted perception influences braking performance and passenger comfort, ultimately contributing to the development of human-centric connected and automated vehicle systems that optimize not only safety and efficiency, but also ride comfort.

References

[1] O. X. Kuiper and J. E. Bos, "Simulator sickness in automated vehicles," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 60, pp. 567–577, 2019. doi: 10.1016/j.trf.2018.10.022

[2] M. G. da Silva, "Measurements of comfort in vehicles," *Measurement Science and Technology*, vol. 13, no. 6, p. R41, 2002. doi: 10.1088/0957-0233/13/6/201

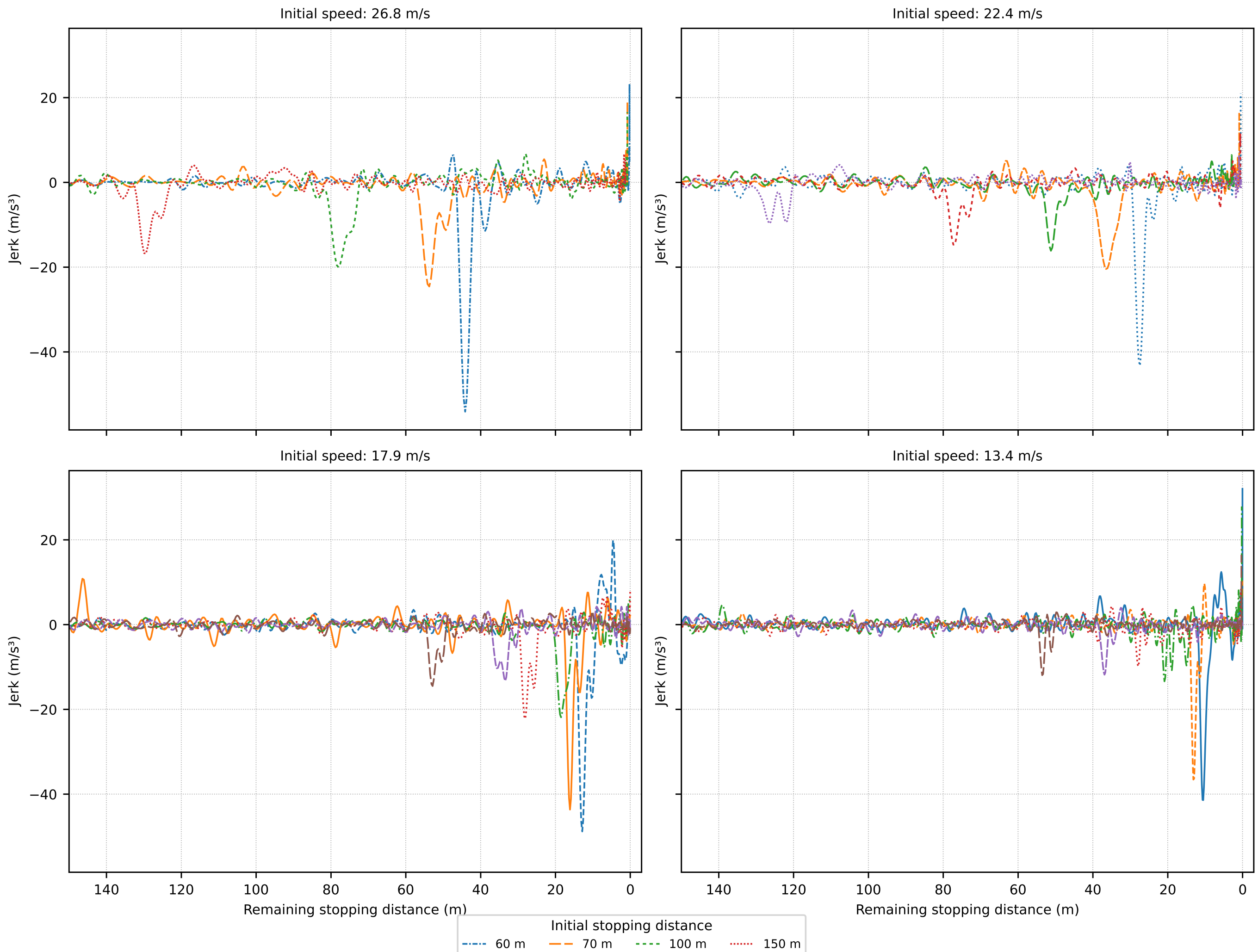

Fig. 6. Jerk profiles across stopping distances

[3] ISO 2631-1:1997, *Mechanical vibration and shock—Evaluation of human exposure to whole-body vibration—Part 1: General requirements*, International Organization for Standardization, Geneva, Switzerland, 1997. [Online]. Available: https://www.iso.org/standard/7612.html

[4] M. J. Griffin, *Handbook of Human Vibration*. London, U.K.: Academic Press, 1990.

[5] M. P. Reed and M. Schneider, "Human motion and posture response to vehicle acceleration," *SAE Int. J. Passenger Cars*, vol. 9, no. 1, pp. 123–135, 2016. doi: 10.4271/2016-01-1469

[6] J. Nilsson, M. Brännström, E. Coelingh, and J. Fredriksson, "Longitudinal and lateral control for automated driving with comfort constraints," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 10, pp. 2913–2924, 2016. doi: 10.1109/TITS.2016.2540662

[7] J. Wei, J. M. Dolan, and B. Litkouhi, "A prediction- and cost function-based algorithm for robust autonomous freeway driving," *Proc. IEEE Intell. Vehicles Symp. (IV)*, pp. 512–517, 2010. doi: 10.1109/IVS.2010.5548052

[8] R. Rajamani, *Vehicle Dynamics and Control*, 2nd ed. New York, NY, USA: Springer, 2012. doi: 10.1007/978-1-4614-1433-9

[9] S. Macenski et al., "Robot Operating System 2: Design, architecture, and uses in the wild," *Science Robotics*, vol. 7, no. 66, p. eabm6074, 2022. doi: 10.1126/scirobotics.abm6074.

[10] W. Guo and T. P. Roth, *Longitudinal and Lateral Motion Data for Ride Comfort Analysis* [Data set], National Institute of Standards and Technology, Gaithersburg, MD, USA, 2026. [Online]. Available: https://doi.org/10.18434/MDS2-4113

[11] W. Guo, S. Kedia, T. Roth, Z. Kootbally, N. Harishchandrakar, E. Griffor, and H. Hajjaj, "Experimental Setup for the Comfort Evaluation in Automated Vehicle: Design and Implementation Framework," *NIST Interagency/Internal Report (NISTIR)*, National Institute of Standards and Technology, Gaithersburg, MD, USA, 2026. [Online]. Available: https://doi.org/10.6028/NIST.IR.8612

[12] M. Green, "How long does it take to stop? Methodological analysis of driver perception–brake times," *Transportation Human Factors*, vol. 2, no. 3, pp. 195–216, 2000. doi: 10.1207/STHF0203_1.

[13] D. B. Fambro et al., "Driver perception–reaction time in stopping sight distance design," *Transportation Research Record*, vol. 2673, no. 3, pp. 1–11, 2019. doi: 10.1177/0361198119833543.