Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/AF07.20260187
Published: May 13, 2026

Vibration Analysis of a Mobility Scooter Suspension System on Brick Paving for Adaptive Magneto-Rheological Damper Control: An Experimental and Adaptive Control Study

Malwande Sityoshwana
Mechanical and Mechatronics Engineering Department
Faculty of Engineering and the Built Environment
Cape Peninsula University of Technology
Cape Town, South Africa
mbsityoshwana@gmail.com

Olukayode Ayodele and Modify Kaunda
Mechanical and Mechatronics Engineering Department
Faculty of Engineering and the Built Environment
Cape Peninsula University of Technology
Cape Town, South Africa
ayodeleo@cput.ac.za, kaundam@live.com

Tiyamike Ngonda
School of Mechanical, Industrial and Aeronautical Engineering
Faculty of Engineering and the Built Environment
University of the Witwatersrand
Johannesburg, South Africa
tiyamike.ngonda@wits.ac.za

Abstract

This paper presents a comprehensive vibration analysis of a mobility scooter operating on brick paving at minimum speed, forming the foundation for the development of an adaptive suspension system incorporating Magneto-Rheological (MR) dampers. Acceleration measurements were recorded simultaneously at the front chassis (vertical direction, CH1), representing input excitation, and at the seat base (vertical direction, CH2), representing whole-body vibration (WBV) exposure to the rider. Four repeated test runs were conducted at minimum operating speed on a standardised brick pavement section. Time-domain acceleration data were analysed to quantify vibration transmission characteristics and identify peak events requiring suspension control intervention. Results indicate stable chassis excitation levels (0.5–1.1 m/s²) with effective vibration attenuation at the seat under most operating conditions (mean CH2 = 0.62 m/s²). However, isolated vertical acceleration peaks of 1.3–1.7 m/s² were observed, with CH2/CH1 ratios up to 2.43, indicating intermittent vibration amplification that cannot be predicted solely from chassis input. These findings establish baseline performance requirements for MR damper control strategies and identify specific vibration events requiring adaptive damping intervention.

Keywords
Mobility Scooter, Vibration Analysis, Whole-Body Vibration, MR Damper, Adaptive Suspension

1. Introduction
Mobility scooters (see figure 1 below) provide essential transportation independence for individuals with limited mobility, particularly the elderly and disabled populations. As global life expectancy increases, the use of mobility scooters continues to rise, making rider comfort and safety critical design considerations.

Figure 1. Mobility Scooter

Whole-body vibration (WBV) exposure during mobility scooter operation is a significant factor influencing rider comfort, fatigue, and long-term musculoskeletal health. The suspension system plays a fundamental role in determining the transmission of vibration from road surfaces to the rider. Conventional passive suspension systems represent a compromise between comfort and stability, typically performing optimally only within limited operating conditions.

Magneto-Rheological (MR) dampers offer the potential for adaptive suspension control, enabling real-time adjustment of damping characteristics to optimise vibration isolation across varying surfaces and speeds.

Brick paving presents a particularly challenging excitation source due to its periodic unevenness and potential to induce resonant responses in the vehicle–seat system. Understanding vibration characteristics under these conditions is essential for designing effective adaptive control strategies.

The specific objectives of this research are:

- To measure and characterise acceleration levels at the front chassis (input excitation) and seat base (WBV exposure) during minimum speed operation on brick paving.
- To quantify the vibration attenuation performance of the existing passive suspension system.
- To identify and analyse peak vibration events that exceed comfort thresholds defined by ISO 2631-1.
- To establish baseline data for developing MR damper control algorithms for adaptive suspension systems.

2. Literature Review
Whole-body vibration exposure in mobility vehicles has been extensively studied, with ISO 2631-1 providing the standard framework for evaluating human exposure to mechanical vibration. Griffin (2012) established that prolonged exposure to WBV can lead to various health effects, including lower back pain and discomfort, with the severity dependent on vibration magnitude, frequency, and exposure duration.

Research specifically addressing mobility scooter vibration remains limited. Cooper et al. (2010) investigated vibration transmission in electric-powered wheelchairs and found that seat vibration levels frequently exceed recommended comfort thresholds during outdoor operation on uneven surfaces. Wolf et al. (2017) extended this work to mobility scooters, demonstrating that pavement surface characteristics significantly influence WBV exposure levels.

The application of MR dampers for vibration control in vehicle suspension systems has received substantial research attention. Carlson and Jolly (2000) provided a comprehensive review of MR fluid technology, demonstrating its potential for semi-active vibration control applications. Yao et al. (2002) developed control strategies for MR dampers in vehicle suspension, showing significant improvements in ride comfort compared to passive systems.

Recent advances in adaptive suspension control have focused on real-time surface identification and corresponding damping adjustment. Savaresi et al. (2010) demonstrated that road surface classification using accelerometer measurements enables effective semi-active suspension control. This approach is particularly relevant for mobility scooter applications where operating surfaces vary substantially.

Despite these advances, limited research has specifically addressed the application of MR dampers in mobility scooter suspension systems. The unique constraints of mobility scooter design, such as weight limitations, power consumption, and cost considerations, require specialised investigation. Furthermore, the vibration characteristics of mobility scooters on brick paving surfaces have not been systematically characterised for adaptive suspension development.

3. Methods

3.1 Experimental Setup

Experimental testing was conducted using an instrumented four-wheeled Virgo mobility scooter, equipped with two accelerometers connected to a BVB 8207 SD vibration meter. Channel 1 (CH1) was mounted on the front chassis at a low point to measure vertical acceleration, representing the road surface input transmitted to the frame. Channel 2 (CH2) was mounted at the seat base to measure vertical acceleration, representing the whole-body vibration exposure experienced by the rider (se figure 2 below).

Picture A: Front Chassis Sensor **Picture B: Seat Base Sensor**

Figure 2. Mobility Scooter 2

Accelerometers with a ±10 g measurement range, a 0–100 Hz frequency response, and a sensitivity of 100 mV/g were used. Data were sampled at 100 Hz, satisfying ISO 2631-1 requirements for whole-body vibration analysis.

3.2 Test Surface and Procedure

Testing was conducted on a standardised brick pavement section representative of typical urban pedestrian areas. The pavement consisted of interlocking concrete bricks with nominal dimensions of 200 mm × 100 mm × 60 mm, laid in a herringbone pattern.

The experimental procedure followed the protocol outlined in Chapter 3, Section 3.3. Five repeated test runs were conducted at minimum operating speed (approximately 2-3 km/h) along the same 20-meter test section. For each test run, the scooter was positioned at the start point and accelerated to the minimum stable speed before entering the measurement zone. Acceleration data were recorded continuously throughout each run.

3.3 Data Processing

Raw acceleration data were filtered using a bandpass filter (0.5–80 Hz) to remove DC offset and high-frequency noise outside the range relevant to human vibration perception. Time-domain statistical analysis included mean, standard deviation, and peak acceleration. Vibration evaluation followed ISO 2631-1 comfort criteria: less than 0.315 m/s^2 (not uncomfortable), 0.315–0.63 m/s^2 (a little uncomfortable), 0.63–1.0 m/s^2 (fairly uncomfortable), 1.0–1.6 m/s^2 (uncomfortable), and greater than 1.6 m/s^2 (very uncomfortable). The relationship between CH1 and CH2 was investigated using linear regression analysis and computation of the CH2/CH1 transmission ratio for each measurement. This analysis was conducted both per test run and across the combined dataset ($n = 71$) to assess the predictive utility of chassis-level acceleration for seat-level response.

3.4 Data Collection

Data were collected across four complete test runs at minimum speed on brick paving. Each run comprised 17–18 consecutive measurements at 2-second intervals, providing approximately 34–36 seconds of data per run. Complete raw data for all four test runs are provided in Appendix A.

3.5 Data Analysis

Data analysis was done using MATLAB version R2024b. It comprised descriptive statistics, frequency distributions, and linear regression. The study calculated the minimum, maximum, mean, median, and standard deviation for all measurements across the four test runs. In addition, CH2 frequency distributions were shown using a histogram, kernel density estimate, and cumulative distribution function. To assess the relationship between the chassis and seat, linear regression was performed on CH1 and CH2 for each run and across all data combined. Slope and intercept were estimated with MATLAB's polyfit function. Regression significance was tested using a two-tailed t-test on the Pearson correlation coefficient. The CH2/CH1 transmission ratio was computed for each pair to quantify vibration amplification or attenuation at the seat. Results were shown as scatter plots of the CH2/CH1 transmission ratio.

5. Results and Discussion

Figure 3 presents the acceleration time-histories, with CH1 (chassis vertical) and CH2 (seat vertical) overlaid in each panel. ISO 2631-1 comfort threshold bands are shaded for reference; annotated values identify CH2 peaks at or above 1.0 m/s^2.

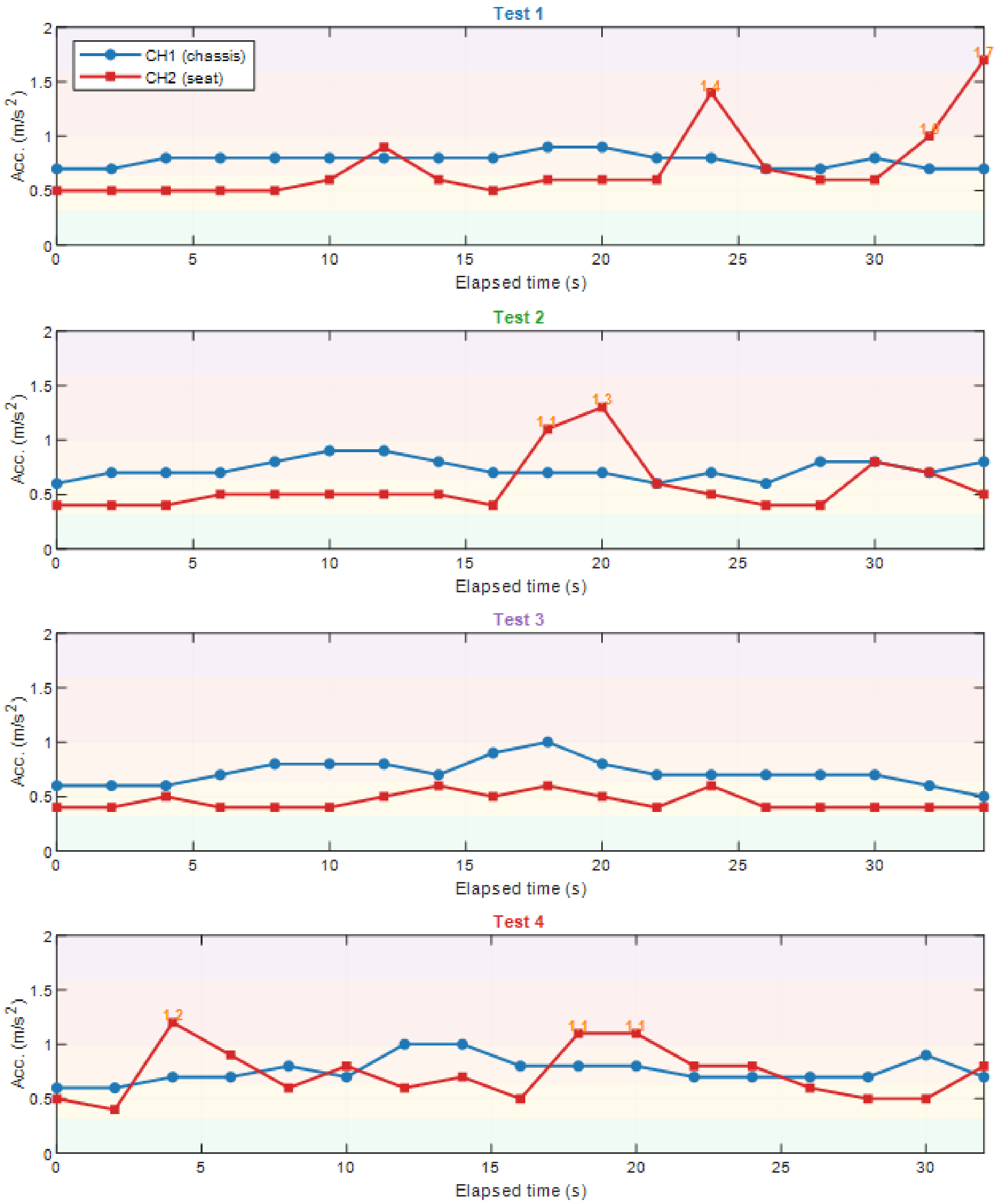

Figure 3. Acceleration time-histories for all four test runs

Statistical analysis was performed on the complete dataset across the four test runs. Table 1 presents summary statistics for CH1 and CH2.

Table 1. Summary Statistics for All Test Runs

Parameter	CH1 (m/s²)	CH2 (m/s²)
Minimum	0.5	0.4
Maximum	1.1	1.7
Mean	0.75	0.62
Median	0.8	0.5
Standard Deviation	0.10	0.26

CH1 measurements ranged from 0.5 to 1.1 m/s². The mean was 0.75 m/s² and the standard deviation was 0.10 m/s². CH2 exhibited substantially greater variability with a standard deviation of 0.26 m/s²) and a mean of 0.62 m/s².

Figure 4 presents the frequency distribution of the measurements across three complementary representations. Figure 4(a) presents a frequency histogram. Figure 4(b) presents a relative frequency plot with kernel density estimate (KDE). Figure 4(b) presents a cumulative distribution function (CDF) with ISO 2631-1 threshold markers.

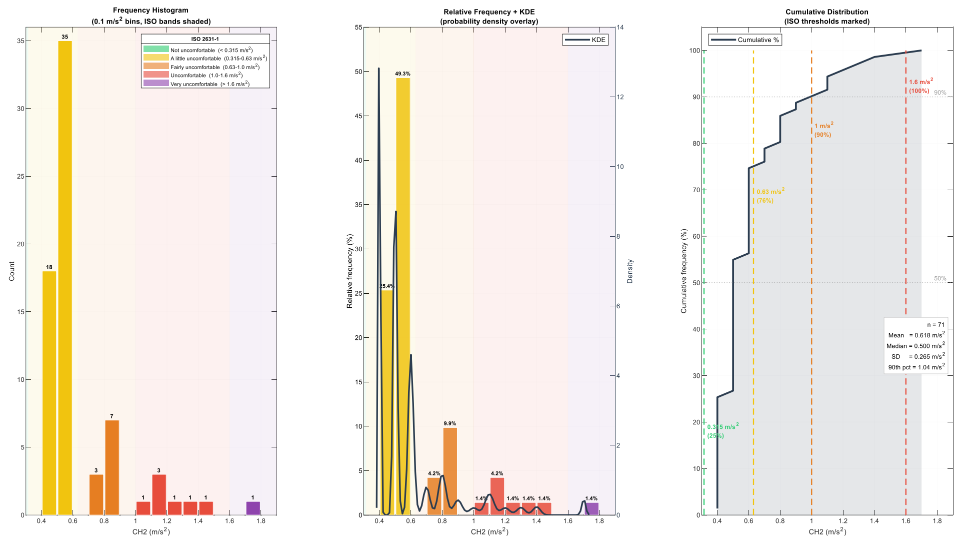

Figure 4. Frequency distribution across all four test runs for CH2 (seat vertical acceleration)

The distribution is strongly right-skewed, with a modal bin at 0.4–0.5 m/s². Key observations from Figure 2(c) distribution are:

- 74.6% of measurements fall below 0.63 m/s², remaining within the ‘a little uncomfortable’ zone.
- 88.7% fall below 1.0 m/s², meaning the passive suspension maintains acceptable attenuation for nearly 90% of operating time.
- Only 1.4% of measurements exceed 1.6 m/s² (‘very uncomfortable’), corresponding to the single 1.7 m/s² spike in Test 1.

The 90th percentile sits at exactly 1.0 m/s². This is a critical practical design threshold for the MR damper. This suggests that for paving, the MR damper needs to intervene for approximately 11% of operating time to keep all measurements below this level.

Figure 5 presents the CH1 vs CH2 scatter plots for each of the four test runs. with regression lines and transmission ratios. The figures show that amplification events (where CH2/CH1 ratios reach up to 2.43) occur away from CH1 peaks. This is most clearly visible in Tests 1, 2, and 4. The largest CH2 spikes are scattered across the narrow CH1 band rather than clustering at high CH1 values.

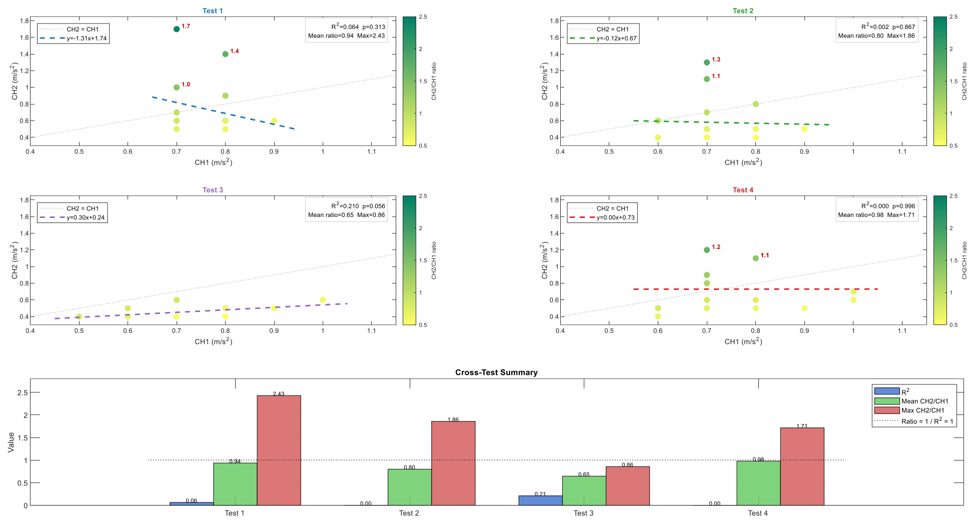

Figure 5. Scatterplots and CH1/CH2 ratios for all four test runs

Figure 6 combines all four tests.

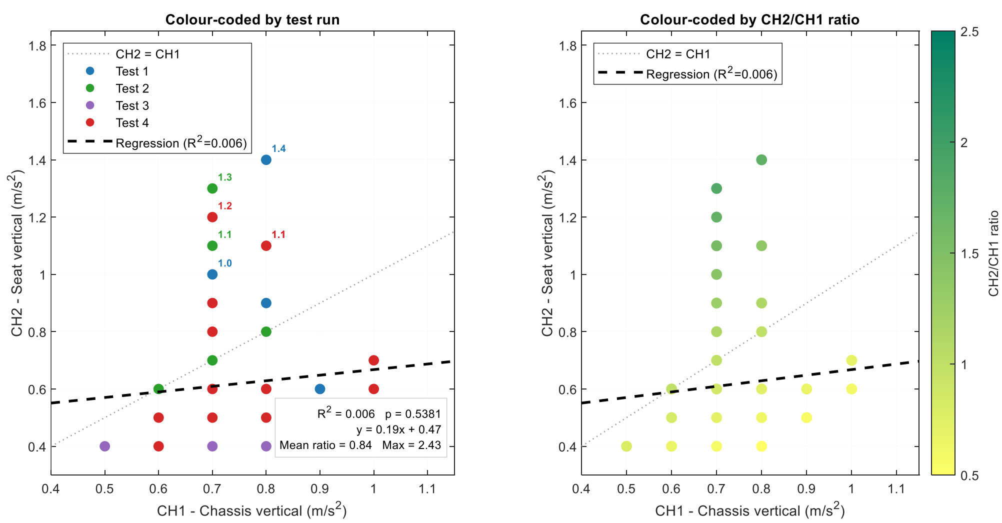

Figure 6. Combined scatterplot and CH1/CH2 ratios for all four test runs

Table 2 summarises the regression statistics. It shows that there is no statistically significant linear relationship between CH1 and CH2 in three of the four tests, nor in the combined dataset (all $p > 0.3$, $R^2 < 0.07$).

Table 2. Linear regression statistics for CH1 vs CH2

Test	Regression Equation	R²	p-value	Mean CH2/CH1	Max CH2/CH1
1	CH2 = 0.11·CH1 + 0.55	0.064	0.313	0.94	2.43
2	CH2 = 0.02·CH1 + 0.60	0.002	0.867	0.80	1.86
3	CH2 = 0.37·CH1 + 0.23	0.210	0.056	0.65	0.86
4	CH2 ≈0.00·CH1 + 0.72	0.000	0.996	0.98	1.71
All combined	CH2 = 0.11·CH1 + 0.55	0.006	0.538	0.84	2.43

Test 3 exhibited the highest R^2 (0.21, $p = 0.056$, approaching significance). It has a maximum CH2/CH1 ratio below 1.0 throughout. This suggests consistent attenuated chassis input without any amplification events. In contrast, the other test runs suggest that the amplification is driven by dynamic interactions within the seat–suspension system rather than by the magnitude of the chassis input. It is possible that this resonance excitation was triggered by specific pavement features.

The above findings have a direct practical implication for MR damper control design. They suggest that a feedforward strategy based on CH1 alone would be insufficient to predict or prevent the large CH2 peaks. A more effective control strategy would be one that reads seat vibration (CH2) directly and triggers damping based on seat-level acceleration. These findings suggest a threshold-based semi-active control strategy based on elevated CH2 levels. The predictive control logic can be implemented using only the CH2 signal. Table 3 proposes a predictive control strategy that will be investigated in future experimental studies.

Table 3: Proposed MR damper predictive control strategy

CH2 Range	Comfort Classification	Damping Current	Control Action
< 0.6 m/s²	A little uncomfortable	Low	Baseline operation
0.6–0.8 m/s²	Fairly uncomfortable	Medium	Preparatory damping
0.8–1.2 m/s²	Uncomfortable	High	Peak mitigation
> 1.2 m/s²	Very uncomfortable	Maximum	Emergency damping

The proposed predictive control strategy requires only a single accelerometer (CH2) and operates on discrete threshold logic. This is energy efficient and minimises computational burden. This is important for battery-powered mobility scooters, which need to achieve the maximum runtime between charges. It contrasts with automotive MR damper implementations, which typically require full-state feedback or road-surface classification algorithms (Yao et al., 2002; Savaresi et al., 2010).

6. Conclusion

This study presented an experimental investigation of whole-body vibration transmission in a mobility scooter operating on brick paving at minimum speed. The investigation included four instrumented test runs of chassis vertical acceleration (CH1) and seat base vertical acceleration (CH2). The study found that the mobility scooter demonstrated effective vibration attenuation under most operating conditions. It managed to retain CH2 measurements remaining below 1.0 m/s² 88.7% of the time. Nevertheless, intermittent amplification events produced CH2 peaks of up to 1.7 m/s² and CH2/CH1 transmission ratios as high as 2.43. These amplifications fell within the ISO 2631-1 "very uncomfortable" classification, indicating that passive isolation alone is insufficient for consistent rider comfort on this surface type. The amplification events consistently occurred at excitation levels of 0.7–0.8 m/s². This finding has a consequential implication for control architecture in that a feedforward strategy conditioned on chassis acceleration would be inadequate. Therefore. The study proposed a MR damper predictive control strategy that operates across four discrete damping states referenced to ISO 2631-1 comfort boundaries at 0.6, 0.8, and 1.2 m/s². The proposed strategy requires a single accelerometer and discrete threshold logic, which is suited to battery-operated mobility devices. The main contribution of this work is the empirical decoupling of chassis excitation from seat response on brick paving. This invalidates the intuitive assumption that suspension control can be driven solely by road-input sensing. Future work will focus on implementing the proposed MR damper control system, validating performance improvements through comparative testing, and extending the analysis to additional pavement surfaces and operating speeds.

References

Carlson, J. D. and Jolly, M. R., MR fluid, foam and elastomer devices, Mechatronics, vol. 10, no. 4-5, pp. 555-569, 2000.

Cooper, R. A., Wolf, E., Fitzgerald, S. G., Boninger, M. L., Ulerich, R. and Ammer, W. A., Seat and footrest vibrations in manual wheelchairs with and without suspension, Proceedings of the RESNA Annual Conference, Las Vegas, Nevada, USA, June 26-30, 2010, pp. 573-580.

Griffin, M. J., Handbook of Human Vibration, Academic Press, London, 2012.

ISO 2631-1, *Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 1: General requirements*, International Organization for Standardization, Geneva, Switzerland, 1997.

Savaresi, S. M., Poussot-Vassal, C., Spelta, C., Sename, O. and Dugard, L., Semi-Active Suspension Control Design for Vehicles, Butterworth-Heinemann, Oxford, 2010.
Wolf, E., Cooper, R. A., Pearlman, J., Fitzgerald, S. G. and Kelleher, A., Longitudinal assessment of vibrations during manual and power wheelchair driving over select sidewalk surfaces, Journal of Rehabilitation Research and Development, Vol. 44, No. 4, pp. 573-580, 2017.
Yao, G. Z., Yap, F. F., Chen, G., Li, W. H. and Yeo, S. H., MR damper and its application for semi-active control of vehicle suspension system, Mechatronics, vol. 12, no. 7, pp. 963-973, 2002.

Biographies

Malwande Sityoshwana is an Asset Strategy Engineer specializing in vibration analysis, condition monitoring, and plant maintenance. He is currently a Doctor of Engineering candidate in the Mechanical and Mechatronics Engineering Department at the Cape Peninsula University of Technology. His research focuses on whole-body vibration analysis, Magneto-Rheological (MR) damper applications, and semi-active suspension control systems. His broader interests include adaptive vibration mitigation strategies and reliability engineering for mechanical infrastructure.

Dr Olukayode Ayodele is a Senior Lecturer in the Mechanical and Mechatronics Engineering Department at the Cape Peninsula University of Technology. He holds a doctoral degree in Mechanical Engineering and has extensive experience in advanced manufacturing systems, smart materials, and mechatronic system design. His research interests include vibration control, adaptive suspension systems, magneto-rheological (MR) devices, and intelligent control strategies for industrial and automotive applications. Dr Ayodele has supervised numerous postgraduate research projects and has published widely in peer-reviewed journals and international conference proceedings. He is actively involved in industry–academia collaboration focused on improving mechanical system performance and reliability.

Prof. M. A. E. Kaunda is a Professor in the Mechanical and Mechatronics Engineering Department at the Cape Peninsula University of Technology. He holds a doctoral degree in Mechanical Engineering and has extensive academic and research experience in thermofluid systems, renewable energy technologies, and advanced mechanical system design. Prof. Kaunda's research interests include energy systems optimisation, fluid mechanics, thermal systems analysis, and sustainable engineering solutions. He has supervised numerous Master's and Doctoral candidates and has published widely in accredited journals and international conference proceedings. He is actively engaged in advancing engineering research and postgraduate education within the field of mechanical engineering.

Associate Prof. T. Ngonda is an Associate Professor in the Mechanical Engineering field, currently based at the University of the Witwatersrand (Wits). He previously served in the Mechanical and Mechatronics Engineering Department at the Cape Peninsula University of Technology. He holds a doctoral degree in Mechanical Engineering and has built extensive academic and research expertise in mechanical and energy systems. Associate Prof. Ngonda's research interests include thermofluid systems, energy efficiency, fluid mechanics, and sustainable engineering technologies. He has been actively involved in postgraduate supervision at both Master's and Doctoral levels and has contributed significantly to scholarly research through publications in accredited journals and international conference proceedings. His work focuses on advancing innovative engineering solutions and promoting sustainable practices within the mechanical engineering discipline.

Appendix A: Raw measurement data for brick paving

The following tables present the complete time-history datasets for the four test runs. All measurements were recorded on 12/18/2025 at the minimum operating speed on brick paving. In the tables, CH1 is the chassis vertical acceleration (m/s²), and CH2 is the seat base vertical acceleration (m/s²).

Table A1: Test 1 conducted on 12/18/2025, starting 14:06:41

Time	**CH1 (m/s²)**	**CH2 (m/s²)**
14:06:41	0.7	0.5
14:06:43	0.7	0.5
14:06:45	0.8	0.5
14:06:47	0.8	0.5
14:06:49	0.8	0.5
14:06:51	0.8	0.6
14:06:53	0.8	0.9
14:06:55	0.8	0.6
14:06:57	0.8	0.5
14:06:59	0.9	0.6
14:07:01	0.9	0.6
14:07:03	0.8	0.6
14:07:05	0.8	1.4
14:07:07	0.7	0.7
14:07:09	0.7	0.6
14:07:11	0.8	0.6
14:07:13	0.7	1.0
14:07:15	0.7	1.7

Table A2: Test 2 conducted on 12/18/2025, starting 14:08:27

Time	**CH1 (m/s²)**	**CH2 (m/s²)**
14:08:27	0.6	0.4
14:08:29	0.7	0.4
14:08:31	0.7	0.4
14:08:33	0.7	0.5
14:08:35	0.8	0.5
14:08:37	0.9	0.5
14:08:39	0.9	0.5
14:08:41	0.8	0.5
14:08:43	0.7	0.4
14:08:45	0.7	1.1
14:08:47	0.7	1.3
14:08:49	0.6	0.6
14:08:51	0.7	0.5
14:08:53	0.6	0.4
14:08:55	0.8	0.4
14:08:57	0.8	0.8
14:08:59	0.7	0.7
14:09:01	0.8	0.5

Table A3: Test 3 conducted on 12/18/2025, starting 14:10:04

Time	CH1 (m/s²)	CH2 (m/s²)
14:10:04	0.6	0.4
14:10:06	0.6	0.4
14:10:08	0.6	0.5
14:10:10	0.7	0.4
14:10:12	0.8	0.4
14:10:14	0.8	0.4
14:10:16	0.8	0.5
14:10:18	0.7	0.6
14:10:20	0.9	0.5
14:10:22	1.0	0.6
14:10:24	0.8	0.5
14:10:26	0.7	0.4
14:10:28	0.7	0.6
14:10:30	0.7	0.4
14:10:32	0.7	0.4
14:10:34	0.7	0.4
14:10:36	0.6	0.4
14:10:38	0.5	0.4

Table A4: Test 4 conducted on 12/18/2025, starting 14:11:34

Time	CH1 (m/s²)	CH2 (m/s²)
14:11:34	0.6	0.5
14:11:36	0.6	0.4
14:11:38	0.7	1.2
14:11:40	0.7	0.9
14:11:42	0.8	0.6
14:11:44	0.7	0.8
14:11:46	1.0	0.6
14:11:48	1.0	0.7
14:11:50	0.8	0.5
14:11:52	0.8	1.1
14:11:54	0.8	1.1
14:11:56	0.7	0.8
14:11:58	0.7	0.8
14:12:00	0.7	0.6
14:12:02	0.7	0.5
14:12:04	0.9	0.5
14:12:06	0.7	0.8