

Track-Time Analysis of Railway Vibration Using Smartphone Sensors: A Case Study on Indonesian Commuter Rail

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ABSTRACT

Railway ride comfort in commuter rail systems is strongly influenced by vibration generated during normal train operation. Conventional vibration monitoring relies on dedicated measurement systems that are often costly and limited in operational flexibility. This study presents a smartphone-based approach for onboard vibration measurement combined with track-time analysis to identify high-vibration zones in Indonesian commuter rail (KRL) services. Vertical and lateral acceleration data were collected during regular passenger operation using a smartphone accelerometer integrated with MATLAB Mobile. Continuous comfort indices (CC_y and CC_z) and event-based indices (Pct and Pde) were evaluated following the EN 12299 framework. The results indicate non-uniform vibration exposure along the route, with representative peaks occurring during train departure from station areas. Vertical vibration reached approximately 0.50 m/s^2 (CC_z), while lateral vibration approached 0.30 m/s^2 (CC_y) during acceleration phases. Event-based analysis identified transient discomfort events with Pct values up to approximately 25.6%, whereas Pde events were less frequent and spatially localised. These findings provide preliminary evidence of the potential of smartphone-based vibration measurement combined with track-time analysis for preliminary ride comfort assessment and maintenance prioritisation in commuter rail operations.

Keywords: railway vibration, ride comfort, smartphone sensors, track-time analysis, commuter rail.

1 INTRODUCTION

Conventional vibration assessment in railways relies on dedicated measurement systems comprising calibrated sensors and data acquisition (DAQ) units. Although these systems provide high measurement accuracy, their high cost and operational complexity limit their use for continuous or large-scale monitoring during regular service (Do et al., 2020; Rodríguez et al., 2021). As a result, vibration evaluation is often confined to short-term campaigns or specialised inspection vehicles.

Recent studies have demonstrated that modern smartphones, equipped with MEMS accelerometers, can be used as a low-cost alternative for vibration and ride comfort assessment in railway applications (Azzoug and Kaewunruen, 2017; Rodríguez et al., 2021). However, existing research has mainly focused on sensor validation and comfort index evaluation, with limited attention given to identifying vibration patterns and high-vibration sections along operational commuter rail routes. In practice, railway operators require information not only on overall vibration levels but also on *where* elevated vibration occurs to support maintenance prioritisation. Direct spatial comparison along commuter rail routes is challenging due to frequent stops and variable operating speeds. A track-time analysis approach, which evaluates vibration as a function of elapsed journey time, offers a practical method to address this limitation under real operating conditions.

Indonesian commuter rail (KRL) services operate under diverse infrastructure and operational constraints, making them a suitable case study for applied vibration monitoring. This study proposes a smartphone-based onboard vibration measurement framework combined with track-time analysis to identify high-vibration zones in KRL services. The findings aim to demonstrate a practical and cost-effective approach for preliminary railway vibration assessment and infrastructure monitoring.

2 LITERATURE REVIEW

2.1 Railway Vibration and Ride Comfort Assessment

Railway vibration is widely recognised as a key factor influencing passenger ride comfort and overall service quality. Vertical vibration, in particular, plays a dominant role in discomfort perception due to its direct transmission through the vehicle structure and passenger seating (Dumitriu and Stănică, 2021). To evaluate ride comfort objectively,

international standards such as ISO 2631 and EN 12299 have been developed, providing frequency-weighted vibration metrics and comfort indices applicable to various railway operating conditions.

Most studies on railway vibration assessment employ dedicated measurement systems consisting of calibrated accelerometers and data acquisition (DAQ) units. These systems enable high-accuracy measurements and have been extensively used in experimental investigations and vehicle dynamic studies. However, their high cost and limited operational flexibility restrict their application in continuous monitoring and large-scale commuter rail operations (Rodríguez et al., 2021).

2.2 Smartphone-Based Vibration Measurement and Track-Time Analysis

Advances in smartphone sensor technology have enabled the use of built-in MEMS accelerometers for vibration measurement in transportation systems. Several studies have demonstrated that smartphone-based sensors can capture vibration characteristics with sufficient reliability for ride comfort assessment when appropriate signal processing is applied (Azzoug and Kaewunruen, 2017). As a result, smartphones have been increasingly explored as a low-cost alternative for vibration monitoring in railway applications (Rodríguez et al., 2021).

Despite these developments, existing research primarily focuses on sensor validation and aggregated comfort indices, with limited emphasis on identifying vibration distribution along operational routes (Do et al., 2020). For commuter rail systems characterised by frequent stops and variable speeds, direct spatial comparison is challenging. Track-time analysis, which evaluates vibration as a function of elapsed journey time, offers a practical approach to identifying high-vibration zones under real operating conditions. However, the application of smartphone-based vibration measurement combined with track-time analysis in commuter rail services remains relatively underexplored, particularly in the context of developing railway systems.

3 METHODOLOGY

3.1 Overall Approach

This study adopts a quantitative, measurement-based approach to evaluate railway vibration using smartphone sensors under normal commuter rail operations. Vertical vibration data were collected onboard KRL services using a smartphone running the MATLAB Mobile application. The recorded signals were processed to obtain vibration metrics in the time domain and analysed using a track-time approach to identify sections associated with elevated vibration levels.

Rather than comparing complete routes or stations, vibration characteristics were evaluated as a function of elapsed journey time. This approach allows the identification of high-vibration zones under real operating conditions, independent of route length or station spacing.

3.2 Data Acquisition

Onboard vibration measurements were obtained using a modern smartphone (iPhone 13 series) equipped with a built-in tri-axial accelerometer. Data acquisition was performed using the MATLAB Mobile application with a fixed sampling frequency of 100 Hz, which is sufficient to capture the frequency range relevant to railway ride comfort assessment after standard filtering.

The smartphone was placed directly on the carriage floor near the door or window area to ensure stable mechanical coupling with the vehicle body and to maintain adequate GNSS reception. The device was positioned flat, with its axes aligned as closely as possible with the longitudinal, lateral, and vertical directions of the vehicle. Measurements were conducted during regular passenger service from origin to destination stations, capturing steady running conditions as well as transient events such as acceleration and braking.

3.3 Data Filtering and Signal Processing

Raw acceleration data were imported into MATLAB for post-processing. Initial data screening was performed to remove start-up transients, handling disturbances, and any segments affected by noticeable sensor movement. Vertical acceleration signals were then filtered to remove bias and high-frequency noise outside the range relevant to ride comfort analysis. To interpret the calculated vibration indices in terms of passenger comfort perception, the threshold values defined in EN 12299 were adopted. Table 1 summarises the comfort classification used in this study.

Table 1 Comfort threshold classification according to EN 12299

Index Value	Comfort Perception	Colour
$CCy(t), CCz(t) < 0.20 \text{ m/s}^2$	Very Comfortable	Blue
$0.20 \text{ m/s}^2 \leq CCy(t), CCz(t) < 0.30 \text{ m/s}^2$	Comfortable	Green
$0.30 \text{ m/s}^2 \leq CCy(t), CCz(t) < 0.40 \text{ m/s}^2$	Medium	Yellow
$0.40 \text{ m/s}^2 \leq CCy(t), CCz(t)$	Less Comfortable	Red

To characterise vibration over time, the filtered vertical acceleration was segmented using a moving-window approach. For each window, the root mean square (RMS) vertical acceleration was calculated, providing a representative measure of vibration intensity during short time intervals.

3.4 Track-Time Analysis and High-Vibration Zone Identification

Track-time analysis was employed to evaluate vibration as a function of elapsed journey time. Station dwell periods were excluded from the analysis to avoid bias from non-running conditions. High-vibration zones were identified by defining threshold exceedances based on statistical criteria, such as windows exceeding the 95th percentile of RMS vertical acceleration values.

The distribution of vibration levels along the track-time domain was visualised using time-history plots, highlighting clusters of elevated vibration. These zones were interpreted as potential comfort-critical sections associated with operational dynamics or track-related irregularities, which may warrant further inspection or maintenance attention.

4 RESULT AND DISCUSSION

4.1 Characteristics of Onboard Vibration during Commuter Rail Operation

Figure 1 illustrates the speed profile and corresponding onboard vibration responses recorded on a KRL service operating along the Jatinegara–Bekasi corridor. The service is characterised by five intermediate station stops, resulting in frequent acceleration, cruising, and braking phases that are typical of urban commuter rail operation. Such stop–go operating patterns are known to influence vibration exposure and ride comfort in commuter rail systems (Peng et al., 2022).

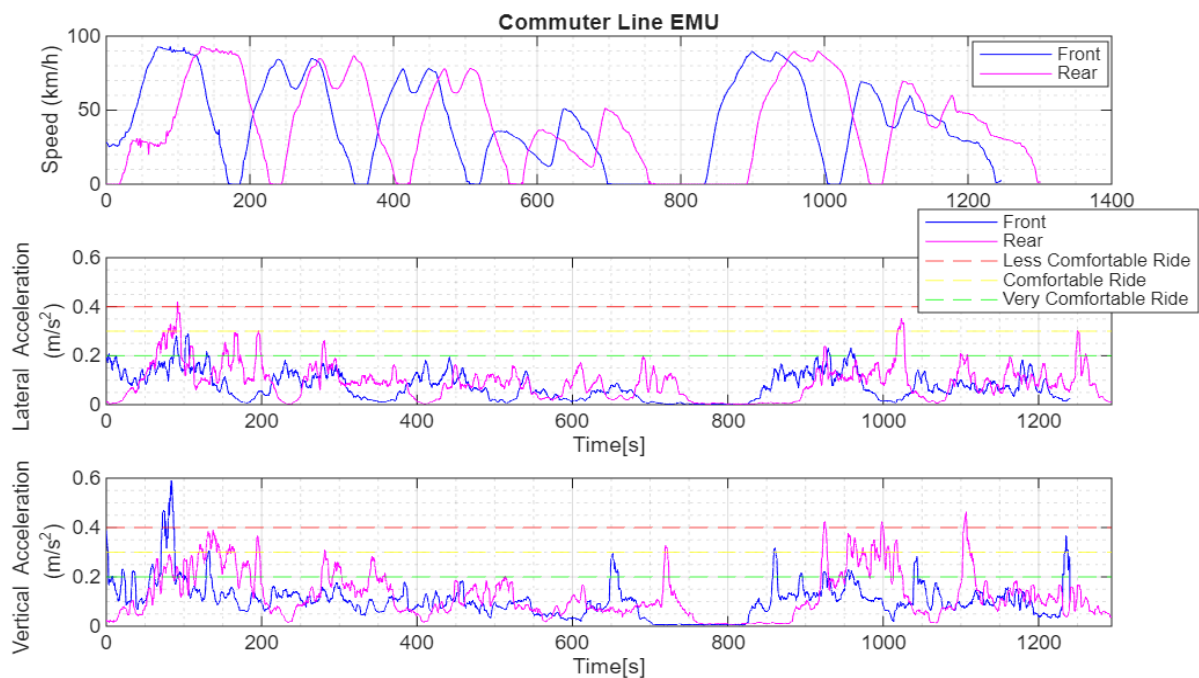


Figure 1 Speed profile and corresponding onboard vibration responses measured using smartphone sensors during a KRL EMU service.

The speed profile demonstrates repeated acceleration–deceleration cycles throughout the journey. This operational characteristic is reflected in the vibration responses, where both lateral and vertical accelerations exhibit pronounced

temporal variability rather than uniform behaviour. Similar non-uniform vibration patterns under in-service conditions have been reported in previous railway vibration studies, highlighting the strong influence of local operational and infrastructure characteristics on passenger vibration exposure (Dumitriu and Stănică, 2021).

Vertical vibration amplitudes are consistently higher than lateral vibration amplitudes, confirming the dominant contribution of vertical motion to passenger discomfort in railway vehicles. This observation is consistent with established findings that identify vertical vibration as the primary contributor to ride comfort degradation in seated passengers (Dumitriu and Stănică, 2021; ISO-2631, 1997). Several vibration peaks exceed the comfort thresholds defined in EN 12299, particularly during phases associated with speed changes, supporting the need for time-resolved vibration assessment rather than route-averaged indicators.

A comparison between front and rear carriages reveals noticeable differences in vibration response, with the rear carriage generally experiencing higher and more frequent vibration peaks. Differences in vibration characteristics along the train consist have been attributed to vehicle dynamic behaviour, force transmission through couplers, and variations in suspension response, as reported in previous experimental and numerical (Peng et al., 2022; Rodríguez et al., 2021). These findings underline the importance of considering carriage position when conducting onboard vibration measurements using passenger-level sensors.

The spatial distribution of elevated vibration levels, shown in Figure 2, further indicates that high-vibration occurrences are not evenly distributed along the route but tend to cluster at specific track-time locations. Similar clustering of vibration exceedances has been observed in studies employing smartphone-based and conventional measurement systems, where localised track features, transitions, or operational manoeuvres were found to govern vibration intensity (Azzoug and Kaewunruen, 2017; Rodríguez et al., 2021). Together, the speed profile, vibration time histories, and spatial mapping demonstrate the suitability of track-time analysis for identifying non-uniform vibration exposure under real commuter rail operating conditions.

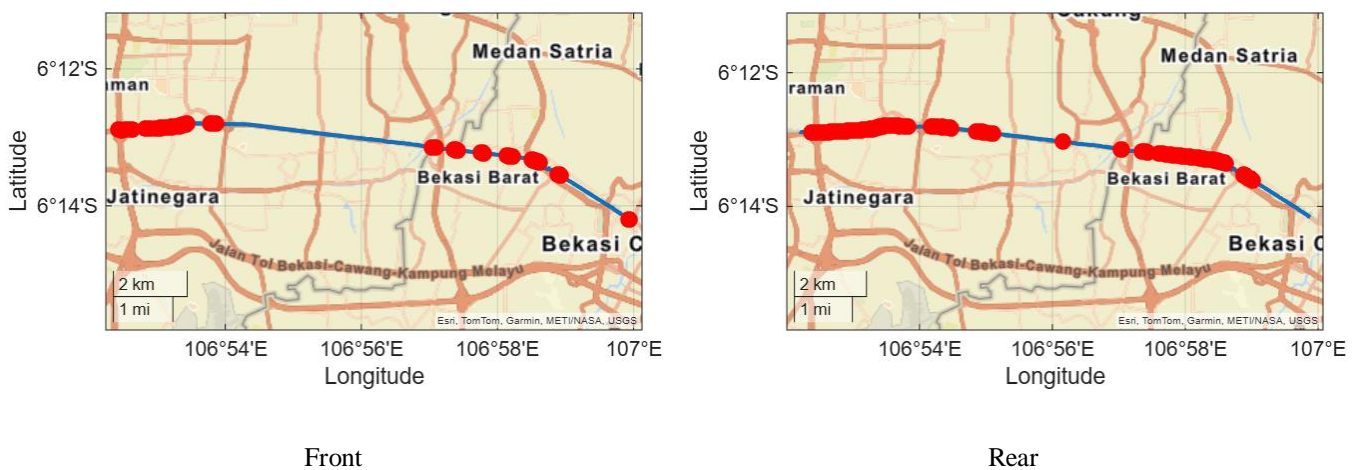


Figure 2 Spatial mapping of onboard vibration exceedances identified using smartphone-based measurements along the analysed KRL EMU service.

4.2 Identification of High-Vibration Zones Using Track-Time Analysis

Figure 3 and Figure 4 present the results of the track-time analysis used to identify high-vibration zones along the analysed KRL EMU service. Continuous comfort indices (CCy and CCz) are first examined to characterise persistent vibration exposure, followed by event-based indices (Pct and Pde) to capture transient discomfort events in accordance with EN 12299.

4.2.1 Continuous comfort exceedances (CCy and CCz)

The Figure 3 of CCz and CCy reveal that vibration exposure is not uniformly distributed along the journey but occurs intermittently at specific track-time locations. Vertical vibration (CCz) exhibits more frequent and higher exceedances than lateral vibration (CCy), confirming the dominant role of vertical motion in passenger ride comfort degradation, as widely reported in railway vibration studies (Dumitriu and Stănică, 2021; Peng et al., 2022).

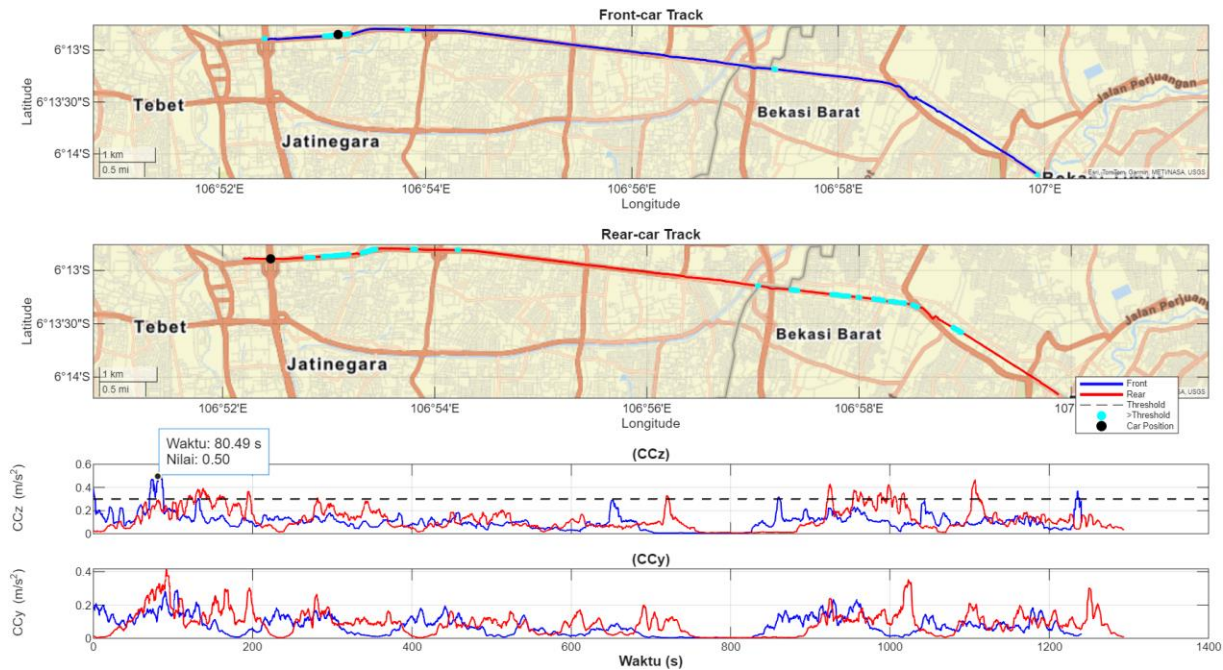


Figure 3 Track–time visualisation of continuous comfort indices (CCz and CCy) for the front and rear cars of the KRL service between Jatinegara and Klender.

A representative peak occurring shortly after departure from Jatinegara station is highlighted to demonstrate the proposed track-time mapping approach. This peak corresponds to elevated CCz values exceeding the comfort thresholds defined in EN 12299 and coincides with the onset of acceleration from standstill. High vibration levels during train departure and arrival phases are commonly observed in commuter rail systems due to the combined effects of traction forces, suspension response, and wheel–rail interaction under transient operating conditions (EN 12299, 2009; ISO-2631, 1997; Rodríguez et al., 2021).

By placing a cursor at this representative peak, the spatial positions of the front and rear carriages can be simultaneously identified. The results show that the rear carriage experiences higher vibration amplitudes than the front carriage at the same track-time location, indicating the influence of train formation effects and force transmission along the consist. This is because the front carriage does not pass through the area traversed by the rear carriage due to the difference in departure points.

4.2.2 Event-based discomfort indicators (Pct and Pde)

The Figure 4 shows that event-based comfort indices provide complementary insight into transient vibration events that may not be fully captured by continuous indices. The Pct and Pde results indicate that discrete discomfort events occur less frequently than continuous vibration exceedances but are more sharply localised in time and space.

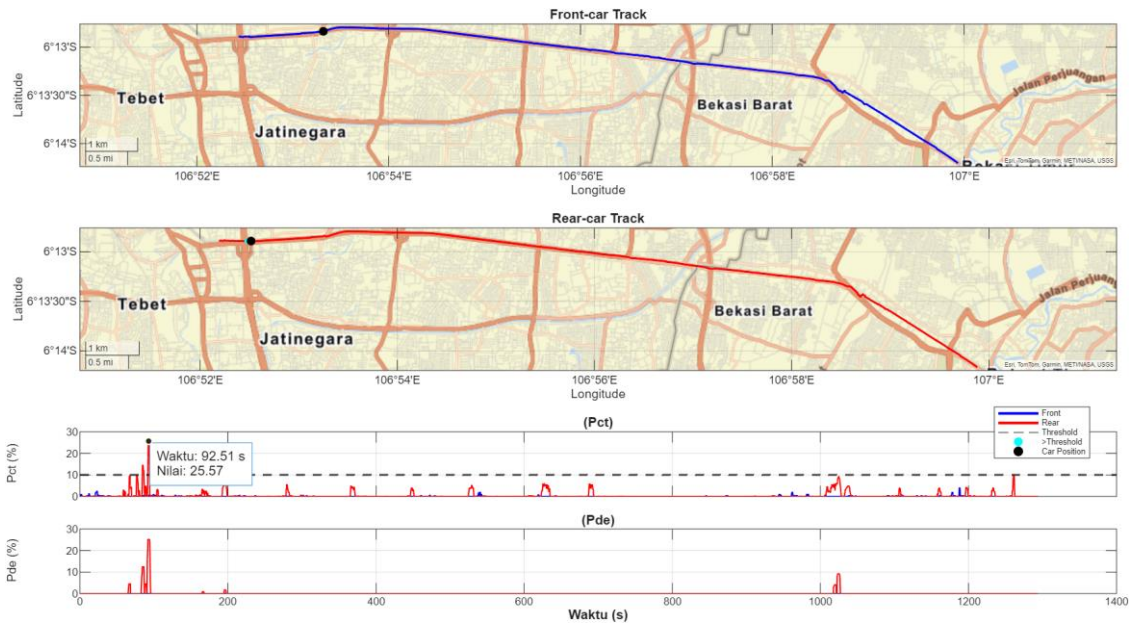


Figure 4 Geospatial position of front and rear cars with corresponding *Pct* and *Pde* for the Jatinegara–Bekasi service

The representative event highlighted near the departure from Jatinegara station is characterised by elevated *Pct* values, reflecting increased lateral dynamics associated with acceleration and track transitions. *Pde* events are observed more sporadically and typically correspond to abrupt excitation, such as localised track irregularities or operational manoeuvres. Previous studies have similarly shown that event-based indices are particularly sensitive to transient conditions occurring near station approaches and departures (Azzoug and Kaewunruen, 2017; Dumitriu and Stănică, 2021).

Although multiple vibration events are observed throughout the journey, highlighting a representative peak is sufficient to demonstrate the capability of the proposed method. This approach avoids over-complicating the visualisation while clearly illustrating how smartphone-based measurements combined with track-time analysis can localise comfort-critical events under real operating conditions.

Overall, the combined use of continuous and event-based indices confirms that elevated vibration levels in commuter rail services commonly occur when trains enter and exit station areas, where transient operational dynamics dominate. These findings support the use of track-time analysis as a practical tool for identifying vibration-critical sections that may warrant further inspection or monitoring.

4.3 Implications for Practice

The results demonstrate that smartphone-based vibration measurement combined with track-time analysis can serve as a practical and cost-effective tool for preliminary vibration screening in commuter rail operations. Although smartphone sensors do not replace certified inspection systems, previous studies have shown their suitability for capturing vibration patterns relevant to ride comfort assessment when appropriate processing is applied (Azzoug and Kaewunruen, 2017; Rodríguez et al., 2021). The observation that elevated vibration commonly occurs during train entry to and departure from station areas highlights the importance of focusing inspection and maintenance efforts on operational transition zones, where traction forces, braking dynamics, and wheel–rail interaction intensify vibration exposure (Dumitriu and Stănică, 2021; Peng et al., 2022). Furthermore, the observed differences in vibration response between front and rear carriages suggest that carriage position should be considered in vibration monitoring strategies. Overall, the proposed approach provides a practical complement to existing railway asset management practices by enabling opportunistic data collection during normal service to support inspection prioritisation and ride comfort improvement.

5 CONCLUSION

This study provides preliminary evidence of the potential of smartphone-based accelerometers for onboard vibration measurement in KRL services. By integrating vibration metrics with a track-time analysis framework, the proposed approach is able to identify sections associated with elevated vibration exposure under normal operating conditions.

The results show that vibration levels are not uniformly distributed along the route and tend to increase during train entry to and departure from station areas, where transient operational dynamics dominate.

The combined use of continuous and event-based comfort indices provides complementary insight into both persistent and transient vibration behaviour. A representative peak highlighted in this study illustrates how track-time mapping can localise vibration-critical events and distinguish differences in vibration response between front and rear carriages. These findings confirm the suitability of track-time analysis for capturing non-uniform vibration exposure in commuter rail systems with frequent stop-go operation.

Although smartphone-based measurements do not replace dedicated inspection systems, they offer a practical and cost-effective solution for preliminary vibration screening and ride comfort assessment. The proposed framework can support maintenance prioritisation and monitoring strategies by enabling opportunistic data collection during regular passenger service. Future work may extend this approach through longer-term data collection, multi-device validation, and integration with detailed track and vehicle condition information to enhance diagnostic capability.

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