Theses of the doctoral (PhD) dissertation

Automotive and mechatronics applications of IMU sensors

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1 Abstract

The unevenness and deterioration of road surfaces have a substantial impact on vehicles, their occupants, and overall traffic safety. Road-induced vibrations can accelerate the wear of mechanical and electronic vehicle components and adversely affect passengers' comfort and health. Consequently, the early detection and repair of pavement irregularities are of great societal and economic importance, and at the same time, the significance of these problems and their impact on our everyday lives also motivated me in my work. Therefore, the research focuses on developing a novel, cost-efficient, and scalable methodology for automated road surface quality assessment using vehicle-mounted vibration sensors and advanced data processing techniques.

In the course of the research, I investigated the information content of vibration data measured at different points on the test vehicles, the applicability of automated labeling methods, and the influence of driver-induced dynamic effects on signal quality.

The recorded signals were processed through a dedicated data pre-processing and feature extraction workflow, which included synchronization, noise filtering, and spectral analysis. Subsequently, I evaluated the pre-processed measurement data using machine learning methods. The analysis demonstrated that the combination of multiple sensor locations significantly improves the accuracy and robustness of the classification model, confirming that signals with different information content can be obtained at different points on the vehicle.

The work also introduced an automated labeling approach based on unsupervised learning, where clustering methods were used to identify internally homogeneous segments of road quality without the need for explicit reference data. This semi-automated annotation process produced consistent and interpretable quality categories, making it suitable for generating training data for supervised learning models.

In addition, the dynamic behavior of the vehicle was analyzed to identify and mitigate the negative effects of aggressive lateral and longitudinal maneuvers on the measurement signals. A detection and correction method was developed to reduce the impact of these unwanted disturbances, thereby increasing the reliability of road surface classification under diverse real-world driving conditions.

Altogether, the research presents a comprehensive methodology for indirect pavement quality assessment based on vibration data, emphasizing the integration of multi-sensor information, automated labeling, and signal correction techniques.

2 Theses

Thesis #1. I investigated the added information content of vehicle cabin and suspension sensor data for vibration-based road surface quality measurement and classification using a custom-developed multi-sensor measurement system.

- I developed and built a data acquisition system for vehicle vibration measurements. The unit is capable of recording tri-axial acceleration and angular velocity inside the vehicle cabin, as well as vertical acceleration on both sides of the rear suspension control arms. The system also logged GPS data for location tracking. Piezoelectric 805M1-0020 accelerometers were mounted on the left and right rear control arms, while an MPU6050 MEMS-based IMU sensor was installed inside the cabin. The main controller was a Raspberry Pi 4B. Additional electronic circuits, including 12-bit MAX186 ADC module and level-shifters, were implemented on custom-designed PCBs.
- I conducted long-term vehicle vibration measurements on public road networks mainly in Zala and Vas counties, including both urban sections and interurban routes connecting major towns. The database therefore contains road segments of widely varying surface quality, ranging from newly built or resurfaced sections to moderately worn and heavily degraded pavements with continuous cracking and potholes. The total length of road segments recorded for training the subsequent unsupervised annotation algorithm was 82 kilometers. After the model training, an additional 267 kilometers of road network

data were used for validation purposes. Measurements were performed using two test vehicles with different suspension architectures, first a 1997 BMW 318is sedan with a fully independent multilink rear suspension, and second a 2019 Nissan Leaf with a torsion beam rear suspension and separated spring–damper elements, supporting the generalization of the findings.

- I processed the raw measurement data through a multistage data processing pipeline developed to filter out measurement errors, normalize signals, and correct for sudden maneuvers and vehicle speed variations. The measured routes were segmented into homogeneous sections based on road surface quality using the Pruned Exact Linear Time (PELT) change point detection algorithm, with automatic identification of homogeneous segments without prior definition of segment length or number. Each segment was characterized by the median and standard deviation of the relevant variables to reduce data dimensionality. The resulting dataset was then processed and evaluated using supervised machine learning models to assess the influence of sensor placement and type on classification performance. Among six tested models, the Random Forest classifier achieved the best performance. After hyperparameter optimization, I trained the final model using the Gini criterion, a minimum split size of 2, a minimum leaf size of 1, and 300 estimators without depth limitation. The model classified road sections into four quality categories, ranging from severely degraded to newly resurfaced surfaces. The final classification accuracy was 91.2%, and the area under the ROC curve (ROC–AUC) was 98.6%.

- Through Principal Component Analysis, feature importance metrics, and SHAP value evaluations of the Random Forest model, it has been established that vibration data measured on the suspension control arms contribute significant additional information compared to cabin-mounted sensors. The incorporation of suspension acceleration data resulted in a 6.9% increase in classification accuracy compared to models trained exclusively on cabin acceleration and angular velocity signals. The results confirmed the necessity of multi-location sensor configurations, as different measurement axes and mounting positions provide critical information depending on specific road surface conditions. I determined that the most influential variables are the vertical and lateral accelerations measured in the cabin, the angular velocity around the longitudinal axis in the cabin, and the vertical acceleration measured on the left rear control arm.

Related publications: 1, 2, 3, 8

Thesis #2. I introduced and evaluated the applicability of a Machine-In-the-Loop (MIL) annotation method for vibration-based road surface quality classification.

- Due to the absence of ground-truth annotations for the measured road sections, a semi-automated Machine-In-the-Loop annotation approach was developed.The proposed method is based on an unsupervised machine learning algorithm, wherein a Gaussian Mixture Model was employed to cluster vibration segments lacking reference labels. The clustering model utilized all vibration-

related variables of the pre-segmented road sections obtained through the PELT change point detection algorithm. During model fitting, the maximum number of iterations was set to 300, the covariance type was defined as "full," the tolerance threshold was set to 10^{-4}, and the initialization method was "k-means."

- I demonstrated that the developed MIL-based clustering algorithm was capable of grouping road sections of varying lengths into coherent clusters that exhibited internal homogeneity in terms of vibration and surface quality characteristics, without spatial resolution limitations. In addition to manual verification, the optimal number of clusters and thus the number of distinguishable road quality classes were determined based on statistical metrics of the clustering model, including the Bayesian Information Criterion (BIC), Akaike Information Criterion (AIC), Silhouette score, and Log-Likelihood score. The first three indicators were analyzed using the elbow method for values of K between 2 and 9, which were selected based on industry standards and previous empirical practice.
- The elbow analysis revealed that both BIC and AIC values decreased with increasing K cluster number, indicating improved model fit; however, a plateau was observed beyond K = 5 to 6. The Silhouette score reached its maximum between K = 3 and 5, followed by a steep decline, indicating reduced cluster interpretability beyond this range. I established that the balance between model complexity and cluster robustness was achieved for ≤ 3 K ≤ 5. These class numbers are consistent with industry practice, providing both interpretable quality categories

and sufficient differentiation for maintenance decision-making. I evaluated the confidence of cluster assignments through the cumulative probability distribution, demonstrating that for four identified quality classes, approximately 80% of all data points were assigned to clusters with confidence above 90%. The supervised learning model trained on the MIL-labeled dataset accurately captured the underlying vibration–surface quality relationships and achieved strong classification performance. Consequently, it has been established that the proposed Machine-In-the-Loop annotation approach is suitable for generating reliable training data for supervised models in vehicle vibration-based road surface quality assessment.

Related publications: 4, 9

Thesis #3. I investigated the negative impact of lateral and longitudinal aggressive vehicle maneuvers on vibration-based road surface quality assessment and introduced a detection and correction method to mitigate the signal-distorting effects of such abrupt maneuvers.

- I analyzed the occurrence and effects of aggressive vehicle maneuvers that adversely influence vibration-based road quality evaluation. A machine learning–based algorithm was developed to detect such abrupt driving events, focusing on four primary maneuver types: left turn, right turn, sudden braking, and sudden acceleration. For model training, a dedicated dataset was collected over a total distance of 31 kilometers, containing approximately 70% straight and 30% curved road sec-

tions. In total, 340 longitudinal and 200 lateral maneuvers were labeled across both test vehicles. Due to the underrepresentation of lateral maneuvers, oversampling was performed using the Synthetic Minority Oversampling Technique (SMOTE), generating 150% additional synthetic observations from each sample. The labeled thresholds were defined as 7 m/s^2 for acceleration, 10 m/s^2 for braking, and 5 m/s^2 for turning both directions. I trained a multiclass Support Vector Machine classifier to detect the type of aggressive maneuver. The model employed a polynomial kernel with a gamma value of 300 and a kernel degree of 3. The results demonstrated higher accuracy for lateral maneuvers, with the right-turn class exhibiting the lowest error rate. Longitudinal maneuvers, such as braking and acceleration, yielded slightly higher errors, particularly for the hatchback vehicle, which may be attributed to its softer suspension characteristics. The mean classification error was 7.3% for the Nissan Leaf and 6.7% for the BMW 318is, resulting in an overall average classification accuracy of 93%.

- Based on the detected maneuvers, the occurrence and impact of aggressive maneuvers in vibration-based road surface evaluation were analyzed. I established that such maneuvers can occur on both curved and straight sections, often as a result of sudden traffic changes. It was observed that these abrupt accelerations, braking, or steering events may distort the vibration signals and negatively affect road surface classification accuracy.
- SHAP-based analysis of the previously trained classification model showed that during normal, steady driving on straight roads, the dominant features influencing classifi-

cation were vertical acceleration and longitudinal angular velocity, both of which are directly related to the pavement condition. However, during sudden turning maneuvers, the dominant signal component shifted to the yaw angular velocity around the vertical axis, which represents vehicle motion rather than road quality. These observations confirmed that maneuver detection and subsequent correction are necessary to maintain the reliability of vibration-based road quality assessment under diverse driving conditions. Longitudinal maneuvers primarily distort the accelerometer signal along the longitudinal axis, while lateral maneuvers mainly affect the gyroscope data along the vertical axis due to increased yaw motion during cornering.

- To mitigate the signal-distorting effects of aggressive maneuvers, I introduced a correction method based on the SHAP analysis results. A rule-based decision tree logic was constructed to proportionally dampen the signal components most affected by the detected maneuvers. For abrupt lateral maneuvers, the transverse acceleration and yaw angular velocity variables were downscaled, while for longitudinal maneuvers, the longitudinal acceleration and pitch angular velocity components were corrected. The correction was applied proportionally to the temporal proximity of the maneuver events, ensuring smooth signal recovery. As a result of this correction method, the overall classification accuracy of the vibration-based road quality model improved by 2.9%.

Related publications: 5, 10, 11

3 Publications related to theses

Articles in international journals

1. R. Nagy, I. Szalai, "Design and Construction of a Vibration Data Acquisition System for Road Vehicles" *Hungarian Journal of Industry and Chemistry*, vol. 48(1), pp. 71-75, 2020, doi: 10.33927/hjic-2020-11.

   Scimago Journal Ranking: Q4, Impact factor: 0.5

2. R. Nagy, I. Szalai, "High-Resolution Road Segment Analysis using a Multi-Sensor Road Quality Classification System" *London Journal of Engineering Research*, vol. 23(1), pp. 9-20, 2023, ISSN: 2631-8474.

   Scimago Journal Ranking: -, Impact factor: -

3. R. Nagy, A. Kummer, J. Abonyi, et al., "Machine learning-based soft-sensor development for road quality classification" *Journal of Vibration and Control*, vol. 30(11-12), pp. 2672-2684, 2024, doi: 10.1177/10775463231183307.

   Scimago Journal Ranking: Q1, Impact factor: 2.4

4. R. Nagy, I. Szalai, "Vehicle maneuver recognition and correction algorithm for road quality measurement system optimization" *Measurement: Sensors*, vol. 38, 101816, 2025, doi: 10.1016/j.measen.2025.101816.

   Scimago Journal Ranking: Q2, Impact factor: -

5. R. Nagy, I. Szalai, "Development of an unsupervised learning-based annotation method for road quality as-

sessment" *Transportation Engineering*, vol. 21, 100358, 2025, doi: 10.1016/j.treng.2025.100358.

Scimago Journal Ranking: Q1, Impact factor: -

Articles in conference publications

6. R. Nagy, I. Szalai, "Gépjárművekben alkalmazható vibrációs adatgyűjtő rendszer tervezése és építése" *XXVII. Nemzetközi Gépészeti Találkozó (OGÉT), Nagyvárad*, 27, 2019, ISSN: 2068-1267.

7. R. Nagy, I. Szalai, "Személygépjárművekben alkalmazható több szenzoros útfelület minőségmérő eszköz fejlesztése" *XXX. Nemzetközi Gépészeti Találkozó (OGÉT), Székelyudvarhely*, 30, 2022, ISSN: 2068-1267.

Conference abstracts

8. R. Nagy, I. Szalai, "Development of machine learning assisted suspension vibration data-based road quality classification system" *19th IMEKO TC10 Conference "MACRO meets NANO in Measurement for Diagnostics, Optimization and Control", Delft, The Netherlands*, pp 33-39, 2023, ISBN: 9789299009048.

9. R. Nagy, I. Szalai, "Applying data science methods to road vehicle maneuvre detection" *The People Events: 2nd World Conference on Data Science, Amsterdam, The Netherlands*, 17-19.06.2024.

10. R. Nagy, I. Szalai, "Unsupervised learning-based MIL annotation method for road quality assessment" *The People*

Events: 3nd World Conference on Data Science, Amsterdam, The Netherlands, 16-18.06.2025.

11. R. Nagy, I. Szalai, "Development of an unsupervised learning-based annotation method for road quality assessment." *D3A Danish Digitalization, Data Science and AI 3.0, Nyborg, Denmark*, 26-27.08.2025.

Publications not related to theses

Articles in international journals

12. R. Nagy, I. Szalai, "Investigation of the sedimentation characterization of magnetorheological fluids" *Journal of Molecular Liquids*, vol. 390, 123047, 2023, doi: 10.1016/j.molliq.2023.123047.

    Scimago Journal Ranking: Q1, Impact factor: 5.2

Conference abstracts

13. R. Nagy, I. Szalai, T. Fülöp, "Pozíció meghatározása inerciális szenzorokkal" *XXIII. Energetika, Elektrotechnika, Számítástechnika és Oktatás Multi-konferencia, Marosvásárhely*, pp. 41-46, 2022, ISSN: 2734-6757.

14. D. Balogh, S. Mester, R. Nagy, et al., "Gépjármű gyalogossal való ütközése a gyalogos tesztbábu szempontjából" *XXIII. Energetika, Elektrotechnika, Számítástechnika és Oktatás Multi-konferencia, Marosvásárhely*, pp 1-6, 2022, ISSN: 2734-6757.