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# Large-Scale Monitoring of Urban Rail Infrastructure and Operations Using Smartphone Sensing Data

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## Abstract

In recent years, the demand for sustainable, reliable, and high-capacity public transport has increased, particularly in densely populated areas. Urban rail systems, including tram, light-rail and metro networks, can provide an efficient and sustainable means of transport for high-passenger volumes. However, these systems are often characterised by ageing infrastructure, rising energy, staff and material costs, and a shortage of qualified personnel. Together, these constraints increasingly limit operators' ability to maintain a high level of service quality, particularly with respect to infrastructure availability and operational performance. This study investigates how large-scale, low-cost smartphone sensing data, collected by driving personnel during regular service in trams and light-rail vehicles, can support rail infrastructure inspection and maintenance as well as overall operational quality. The results demonstrate that this low-cost smartphone-based sensing approach enables effective monitoring of infrastructure degradation and supports the planning of maintenance interventions. Furthermore, the data can be used to identify safety-critical traffic situations and to assess operational performance.

**Keywords:** smart sensing, smartphones, data analysis, tram, light-rail, operations, infrastructure, condition monitoring

# 1 Introduction

Urban rail transport plays a central role in the transition towards sustainable, high-capacity mobility in densely populated areas. In response to increasing global urbanisation, rail-based urban transit systems are expected to expand further to meet growing mobility demand [1, 2]. Simultaneously, many urban rail operators are facing increasing pressure due to ageing assets, limited maintenance resources, rising operating costs, staff shortages, and growing expectations regarding service quality. In addition, rail infrastructure must become more resilient against climate change and cyberattacks.

To maintain a high level of infrastructure availability and operational reliability, operators require continuous knowledge about the condition of their vehicles and track. To address these challenges more effectively, greater automation in track inspection and maintenance is required to improve staff productivity. At present, many of the required tasks in urban rail transport are still performed manually. Significant upfront investment costs for advanced equipment, together with limited overall funding, can prevent operators from transitioning from manual to automated processes.

To facilitate adoption, low-cost cloud-based sensing solutions offer new opportunities to enhance urban rail operations. Many operators already use smartphones or tablets to support rail operation. These devices contain multiple sensors, including accelerometers, gyroscopes and GNSS receivers, which can be used to record vehicle dynamics and position information during regular service. If deployed systematically, such devices can provide frequent, spatially extensive, and cost-effective monitoring of assets reducing the need for dedicated measurement runs or additional specialised hardware. While not all inspection tasks can be performed using these devices, they can provide operators with a clearer overview of the condition and evolution of their track infrastructure. They can also support the partial automation of regular track inspection and help to prioritise track segments that require more detailed assessment using traditional measurement equipment.

It has already been shown that smartphone accelerometers provide precise enough data to assess track quality. Typically, the built-in sensors provide a flat frequency response up to approximately $20\,\mathrm{Hz}$ to $50\,\mathrm{Hz}$ depending on the device, which is enough to capture relevant track irregularities [3]. Several studies have already shown that smartphones or similar devices can be used to assess track quality [4, 5, 6, 7]. This study extends previous results by using a large-scale dataset of smartphone monitoring data that was collected by driving personnel during regular tram and light-rail services in Frankfurt am Main, Germany, over the course of three years. In addition, the study shows how the data can also be used to identify traffic hazard hotspots and analyse operations. The remainder of this paper is structured as follows. Section 2 describes the deployed sensing set-up, data precessing workflow, and map-matching procedure. The subsequent case studies present applications for monitoring track quality and operational quality. Finally, Section 4 briefly summarises the main findings and discusses the potential of smartphone-based monitoring for urban rail transit.

## 2 Methodology

To collect the required data, three dedicated smartphones are deployed in the urban rail network of Frankfurt am Main, Germany. The urban rail network in Frankfurt am Main consists of a dedicated 67 kilometres long tram and a 65 kilometres long light-rail network. As most lines are double-tracked, the total track length amounts to approximately 250 kilometres. The smartphones are equipped with a dedicated data-recording application that records triaxial acceleration, rotational velocity, magnetic field data, and GNSS-based position and velocity. In addition, metadata, such as the vehicle number and smartphone placement, can be entered when initiating a measurement. The driving staff is advised to place the smartphone always at the same position on the driver's desk and with the same orientation w.r.t. the vehicle. Driving staff can carry the smartphone during their regular shifts, start the measurement at the beginning of the shift, and stop it at the end of the shift. Afterwards, the measurement data is automatically uploaded to a cloud-platform for further processing via WiFi or mobile data. So far, more than 3000 individual measurements have been recorded over the course of approximately three years.

The data are evaluated daily on a cloud platform before being presented to users via a web application, see fig. 1. First, the data are assessed for plausibility and quality, including the correct alignment of the smartphone, sufficient GNSS coverage, and sufficient recording length. Measurements that do not meet these criteria are excluded from further analysis. The remaining measurements are then divided into shorter trips based on speed and stop-duration thresholds. If the vehicle remains stationary for more than two minutes, the measurement is split at that point. This ensures that each measurement segment is associated only with a single line and direction of travel. Then a custom-developed map-matching algorithm [8] is applied to each trip to identify the travelled line and direction and associate each data point with a corresponding node in the digital twin of the rail infrastructure. The digital twin is based on OpenStreetMap data and is enriched with additional nodes at approximately one-metre intervals along the track. The nodes can be assigned tags indicating, for example, the location

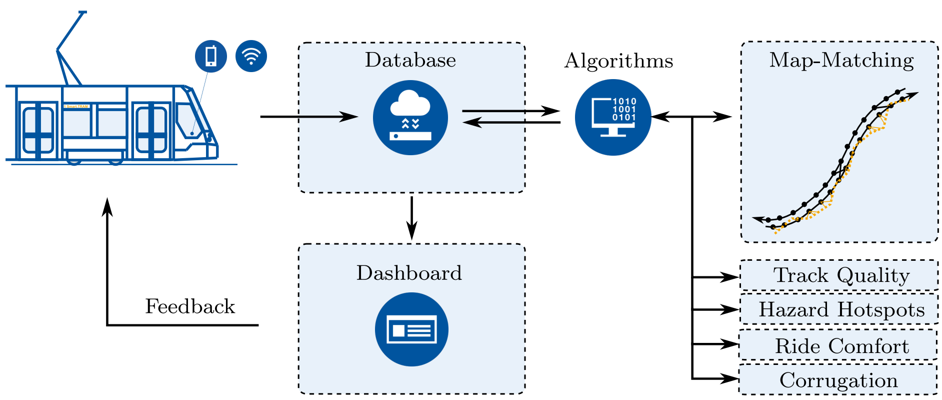



Figure 1: Overall concept of the developed smartphone-based monitoring solution.

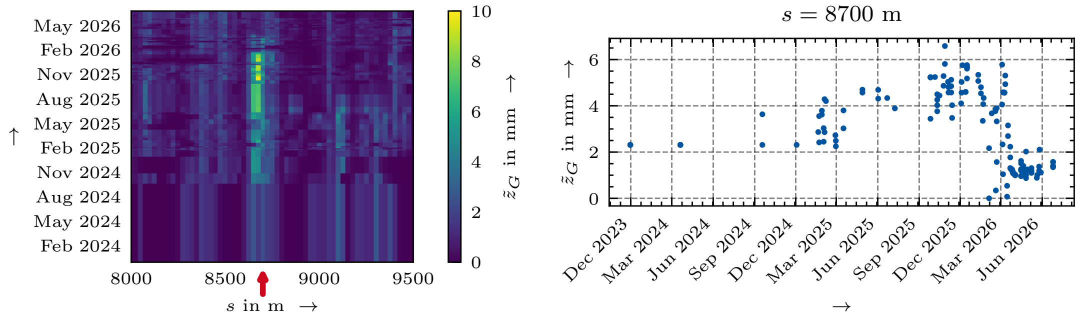
of turnouts, stations, or level crossings. They can also be associated with the lines to which they belong. Using the map-matched data, results can be queried not only in the time domain but also the distance domain along tracks or track segments of a selected line.

# 3 Case-Studies

The following section presents the results of two case studies using smartphone-based sensing data. In the first case-study, the data are used to monitor track quality in terms of vertical track irregularity, which can be estimated from vertical smartphone acceleration using a simplified approach. By applying the digital twin methodology, the results demonstrate how this approach can be used to monitor track degradation in selected sections of interest. In the second case study, the data are used to provide insights into tram operational quality. In this case study, two examples illustrate how measurements of longitudinal acceleration and vehicle speed can be utilised. The first example shows how hazardous locations associated with an increased risk of accidents can be identified from the data. The second example demonstrates how stop durations can be monitored at each station along a tram line.

## 3.1 Monitoring of Track Quality

In [9], a method was developed to approximate the vertical track irregularity $z_G$ from the vertical acceleration $a_z$ measured by a smartphone. The algorithm essentially applies a double-integration approach to estimate the vertical displacement of the car body. The resulting signal is then transformed into the distance domain and filtered within the D1 wavelength band defined in EN 13848. To mitigate the influence of vehicle speed, a correction curve is applied to scale the result at each location to a reference speed selected to provide the best agreement with a reference estimate of track irregularity. Typically, reference speeds of $15\,\mathrm{km/h}$ to $20\,\mathrm{km/h}$ provide the best agreement with reference measurements. Although the estimated wavelengths are partly distorted by the vehicle suspension, the results show high reproducibility and repeatability [9]. Figure 2 shows the results of the algorithm for a track section for the duration of more than two years. The estimated vertical track irregularity $z_G$ is queried for each node along the line using the digital twin. Subsequently, the mean value $\bar{z}_G$ is calculated over consecutive $25\,\mathrm{m}$ windows as a measure of overall track quality and account for outliers in the track irregularity estimation. The analysed section contained a pronounced track defect that could be monitored using the collected data. The temporal development at this location is shown in fig. 2b. In this case, the degradation progressed until early 2026, when a speed restriction was imposed on the affected section. The track defect was remediated in the following months. Similarly, other track sections can be monitored. The monitoring data can also be used to assess track renewal work and verify whether the work has been carried out to a satisfactory standard.




(a) Section overview

(b) Local development at $s = 8700\ m$

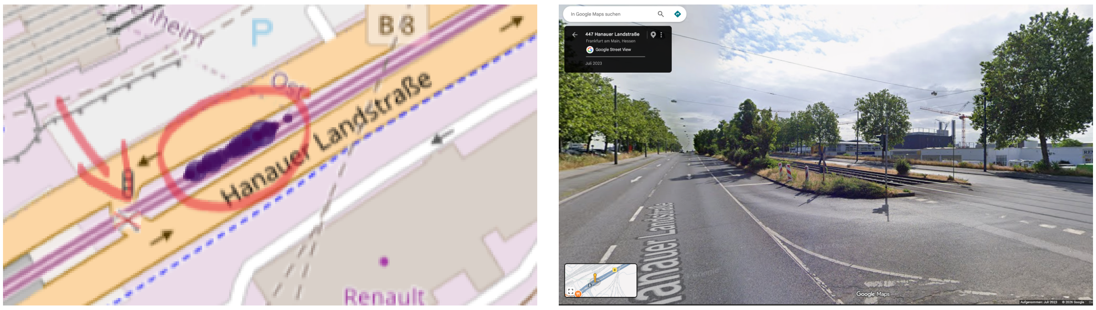
Figure 2: Development of the track quality in a selected track section

## 3.2 Monitoring of Operational Quality

The operational quality of railway services can be assessed using a range of indicators. Examples include ride quality, stop dwell times, punctuality, service availability, and service frequency.

### 3.2.1 Identification of Hazard Hotspots

Ride and service quality are affected, among other factors, by abrupt longitudinal decelerations, which may indicate conflict situations requiring emergency or near-emergency braking. In severe cases, such events may result in accidents. As the smartphones also record longitudinal acceleration, the data can be used to identify potentially hazardous locations by detecting clusters of repeated abrupt braking manoeuvres. The resulting map can be used to analyse the underlying causes leading to hazardous conditions at these locations. In many cases, the identified hotspots occur at locations where motor vehicles, pedestrians or cyclists interact directly with the rail infrastructure. These hotspots are often associated with unfavourable crossing layouts, insufficient sight distances, unclear priority arrangements or traffic signal configurations that create conflicts between rail vehicles and other road users. In Germany, trams and light-rail vehicles travelling at speeds above $30\,\mathrm{km/h}$ must be capable of achieving an emergency braking deceleration of at least $2.04\,\mathrm{m/s^2}$ [10]. Therefore, to identify hazard hotspots, all locations are queried where decelerations reached values of at least $2\,\mathrm{m/s^2}$. The data are then grouped by unique track nodes and further aggregated according to the number of distinct days on which the threshold was exceeded and the mean deceleration recorded at each node. Finally, only nodes at which threshold exceedances occurred on at least two distinct days are retained. Figure 3 shows an example of one such identified hotspot in the light-rail network. In this case, emergency-level decelerations were recorded on five separate days during the monitoring period. The hotspot is located immediately before a level crossing, where the left-turn lane of a four-lane road crosses the tracks. At this location, vegetation between the traffic lane and the track may obstruct sight lines, reducing the ability of




(a) Map-view of the hazard hotspot (b) Google Street View image of the location

Figure 3: Example of an identified hazard hotspot using smartphone monitoring data

both road users and light-rail drivers to anticipate potential conflicts in time. Collisions with left-turning cars are a common issue in urban rail transit [11]. Such collisions can result in substantial repair costs and reduced vehicle availability.

#### 3.2.2 Monitoring of Stop Dwell Times

Another application of the data is the monitoring of stop dwell times based on GNSS velocities recorded by the smartphone. Vehicle stops are first identified using threshold-based criteria. A stop is counted only if the vehicle speed remains below $3\,\mathrm{km/h}$ for more than $3\,\mathrm{s}$. As the measurements are matched to the infrastructure, the closest station can be retrieved for each identified stop. Each station is represented by a single node, typically located near the centre of the platform. A stop is therefore assigned to a station if its location is within 30 metres of the corresponding station node. For each matched stop, the mean stop dwell time and the corresponding standard deviation are then calculated. In addition, stops that cannot be assigned to a station can be analysed to identify locations where frequent unscheduled stops occur and adversely affect tram traffic flow. Figure 4 presents the corresponding mean dwell-time results for one tram line and direction of travel in Frankfurt am Main. The mean dwell times vary substantially between stops. The central station stop exhibits the highest mean dwell time and the greatest variability. At this stop, the platform is shared by several other lines serving the city centre. In addition, heavy car and pedestrian traffic can impede tram movements, further increasing dwell times. Other stops with comparatively long dwell times are also located predominantly in the city centre, whereas the shortest dwell times are observed at stops in the outer sections of the line, outside the city centre. Since each identified stop has a corresponding timestamp, dwell times can also be analysed by hour and day of the week to identify periods with the highest dwell times. Figure 5 shows the corresponding results for the same tram line. Although many measurements were recorded, their temporal coverage is insufficient to represent all days and hours of the week, resulting in gaps in the figure. Nevertheless, slightly higher mean dwell times are observed in the afternoon, coinciding with rush hour. It can also be observed that mean dwell times are also slightly shorter at weekends.

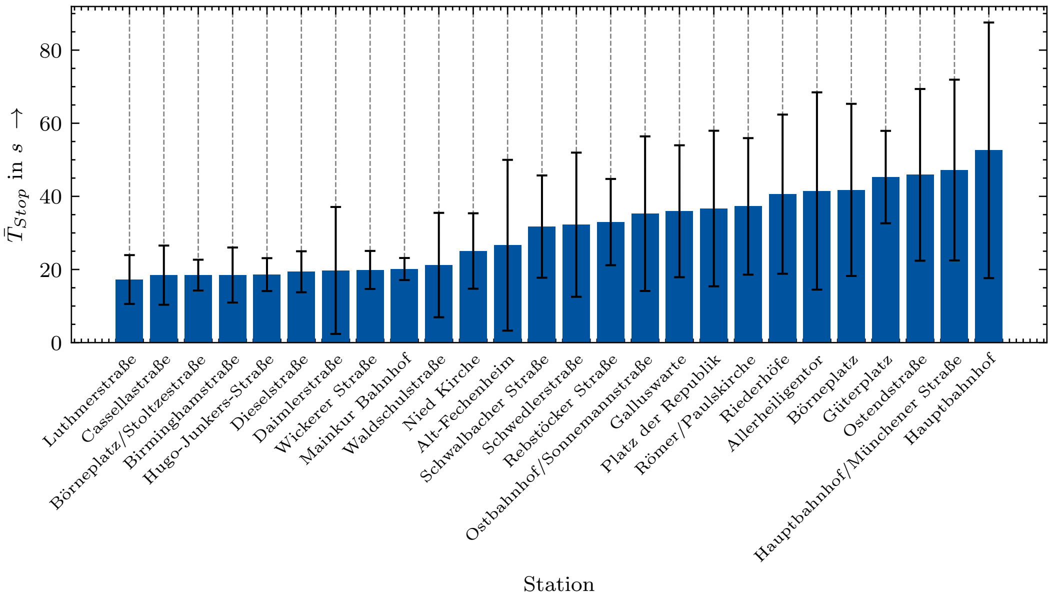



Figure 4: Mean dwell times identified from the smartphone sensing data for several stops on an exemplary tram line in Frankfurt am Main

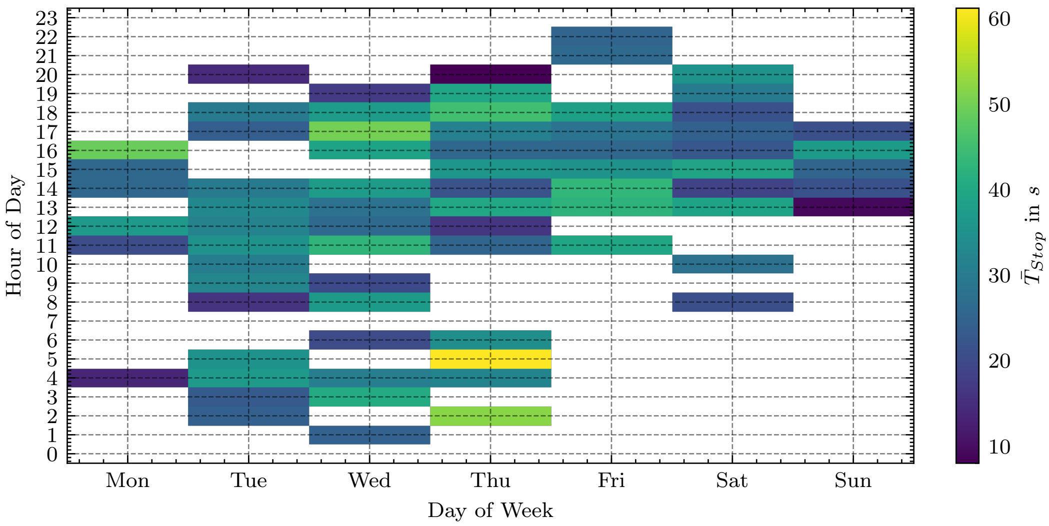



Figure 5: Mean dwell times grouped by weekday and hour of the day for the same line

# 4 Conclusion

This study demonstrated that large-scale smartphone sensing data collected during regular tram and light-rail operation can provide valuable information for monitoring both infrastructure condition and operational quality. The presented case studies showed that vertical acceleration data can be used to estimate changes in track quality and to monitor the temporal development of localised track defects. When combined with a digital twin of the rail infrastructure via a map-matching algorithm, the measurements can be assigned to individual nodes, enabling the data to be queried by line, track section, time period, or other relevant criteria. In addition to infrastructure monitoring, the data were shown to support the assessment of operational quality. Repeated abrupt braking events derived from longitudinal acceleration measurements can reveal locations with an increased potential for traffic conflicts. Such hazard hotspots can provide useful evidence for investigating infrastructure layouts, visibility conditions or traffic signal settings. Furthermore, GNSS-based speed data can be used to identify stops and estimate dwell times at stations, enabling the analysis of operational bottlenecks along individual lines and over different times of day. Overall, the results indicate that smartphone-based monitoring can complement existing inspection and operation analysis in urban rail transit. The approach is not intended to replace dedicated measurement vehicles or detailed manual inspections. Rather, it can provide a continuous overview of network-wide track condition and highlight opportunities for operational optimisation. The smartphone sensing solution can be deployed readily and at substantially lower cost than conventional monitoring systems. Additionally, the algorithms developed in this study are hardware-agnostic and can also be readily deployed on other hardware platforms, as they require only an inertial measurement unit (IMU) and a GNSS receiver. Consequently, the necessary hardware could be integrated directly on board future vehicle fleets. Future work could focus on extending the analysis to larger fleets and integrating the derived indicators more directly into maintenance and traffic management workflows.

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