

Article

Evaluation of Measurement Strategy for Track Side Monitoring of Railway Wheels

Matti Rantatalo , Praneeth Chandran , Florian Thiery , Johan Odelius, Christian Gustafsson, Mathias Asplund and Uday Kumar *

Division of Operation and Maintenance Engineering, Luleå University of Technology, 97187 Lulea, Sweden; praneeth.chandran@ltu.se (P.C.)

* Correspondence: uday.kumar@ltu.se; Tel.: +46-(0)920-491826

Abstract: Wheelsets form an indispensable part of the railway rolling stock and need to be periodically inspected to ensure stable, safe, reliable, and sustainable rail operation. Wheel profiles are usually inspected and measured in a workshop environment using handheld equipment or by utilizing wayside measuring equipment. A common practice for both methods is to measure the wheel profile at one position along the circumference of the wheel, resulting in a one-slice measurement strategy, based on the assumption that the wheel profile has the same shape independent of the measurement position along the wheel. In this article, the representability of a one-slice measurement strategy with respect to the wheel profile parameters is investigated using handheld measurement equipment. The calculated range of standard deviation of the parameters estimated such as flange height, flange width, flange slope, and hollow wear from the measurements shows a spread in the parameter value along the circumference of the wheel. As an initial validation of the results, measurements from the wayside monitoring systems were also investigated to see if a similar spread was visible. The spread was significantly higher for flange height, flange width, and flange slope estimated from wayside measurement equipment than for the same parameters estimated using the handheld measurement equipment.

Keywords: railway wheel; wheel profile; wheel parameters; wayside monitoring; condition monitoring



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1. Introduction

Rail transport has emerged as a significant and sustainable mode of transportation, forming a key enabler of the socioeconomic development of modern society through passenger and freight services. To reduce the carbon emission arising from the transport sector, the European commission aims to shift 50% of medium-distance passenger and freight transports from road transportation to railway and waterborne transport by 2050 [1]. In Sweden, the use of rail transport has increased significantly over the last 26 years, with passenger-kilometer doubled and a 12% increase in freight traffic [2]. An average annual growth of 3% of passenger traffic and 1% of freight traffic is estimated in Sweden up to the year 2050 [3,4]. This growing demand has put a certain strain on the Swedish railway network in terms of operational capacity and service quality. With the rapid development of railway transportation, maintenance and renewal process have become the important factors to ensure a high quality of service (i.e., punctuality, comfort, and safety) [5].

The wheel–rail interface plays a crucial role in the performance of the railway system, and to ensure a high quality of service it needs to be managed well and treated as a system [5,6]. In addition to the rail and wheel, other factors such as track curvature, wheel and rail profiles, friction, and the status of the track and wheel themselves have significant influence on the wheel–rail interface [7]. In Sweden, the track and its components are measured on a regular basis according to internal regulations of the Swedish Transport Administration [3,6,8], and hence infrastructure managers usually have good knowledge

of rail status. However, an infrastructure manager's knowledge of the wheel in service is limited and has become an issue of great relevance in Sweden, as the ownership of the infrastructure and rolling stock is divided.

The wheelset is one of the most important and costly on-maintenance components [9] in the rolling stock, and the health status of the same can be related to operation safety, stability, and noise emission [10]. Wheels are subject to numerous defects that influence their smooth revolutions, and these defects can be broadly classified into four categories: surface defects (flatness, spalling, shelling), profile defects, polygonization (corrugation, roughness, etc.), and subsurface defects [11–14]. The presence of such defects on the wheel can also lead to high-impact forces in the wheel–rail interface, which can subsequently induce damage on the rail and other track components. Further, the presence of such damages can reduce the service life of a wheel, leading to accelerated deterioration and excessive costs. The presence of such damages on wheels can lead to unplanned maintenance activities that are a major source of train delays [15]. Thus, early detection and prediction of wheel defects are essential to reduce systemwide maintenance cost, reduce delays due to unplanned maintenance activities, and ensure safe train operations [16].

The condition assessment of a dynamic system such as a railway wheel can be carried out using various methods: statistical modelling, physical modelling, or condition monitoring. For an in-service train with multiple wheels, the wheel fatigue parameters and wheel wear, and consequently the degradation rate, depend on various factors including varying environmental and operational conditions (speed, axle load, rail profile, etc.). Further, the wheel–rail interaction and the degradation pattern vary between the right and left wheels of an axle, the back and front axles in a bogie, and from bogie to bogie [17–19]. These varying factors hinder the use of numerical, statistical, and analytical models for condition assessment of an in-service wheel. Accordingly, condition monitoring techniques can be considered as the best plausible tool for condition assessment for an in-service wheel.

An imperative step in any condition monitoring process is data acquisition. Assessment of the present condition and forecasting of the future condition of the wheelset strongly relies on the measurement stage, and hence selecting an adequate sensor type for measurement purposes is crucial. For railway wheelset monitoring, the data acquisition approach can be broadly classified into two types of measurement: in-workshop measurement, when the wheels are idle, and in-service measurement, when the wheels are in motion. In-service measurements can be further divided into two types based on the position of the data acquisition sensor: onboard measurements and wayside measurements. Ultrasonic techniques [20,21], infrared camera [22], and magnetic techniques [23–25] are commonly used monitoring tools used during in-workshop measurements of rail wheels. Acoustic techniques [26,27], ultrasonic technique [28], vibration measurements [29,30], and magnetic techniques [31,32] are common types of monitoring techniques used for in-service and onboard inspections of rail wheels. The in-service and wayside inspection of rail wheels commonly makes use of monitoring systems such as strain gauges [33,34], Fibre Bragg grating sensors [35,36], ultrasonic techniques [37,38], vibration technique [39,40], acoustic technique [41], and laser-air hybrid ultrasonic techniques [42]. Most of the studies using the abovementioned techniques have been carried out to detect wheel flats, surface defects, and subsurface defects. However, abnormalities on the profiles of the wheel such as asymmetrically worn wheel and hollow wear are understudied [6,43].

Train wheelsets are subjected to constant wear mainly due to the friction arising during the contact between the wheel and the rail. Once the wear on the wheelset exceeds the safety limit, the wheelsets need to be reprofiled or replaced, otherwise normal wheel–rail interaction will be restricted and can ultimately lead to derailment. Further, asymmetrically worn and hollow-worn wheels can also lead to significant damages on the rail head and in switches and crossings, thus increasing the time and cost for maintenance activities. Hence timely assessment of the wheel profile using suitable condition monitoring techniques is crucial for infrastructure managers to ensure safety and high quality of service. A general criticism of measurement systems, especially the ones used for condition monitoring, is that

they do not always produce reliable data [19]. Instead, they can give measurement values with huge discrepancies from the actual value due to errors or to unreliable measurement patterns [44]. Such a scenario can lead to incorrect assessment resulting in unwanted interventions and wrong or no actions being taken, thus increasing the risk of catastrophic failures and adding to the cost paid by the infrastructure owners. Thus, it is crucial to ensure that the measured data are reliable and of high quality, since the management decisions based on the information derived from the data are only as decisive as the data themselves.

Wheel profiles are usually inspected and measured in a workshop environment using a handheld measurement device, measuring the wheel profile at one position of a non-rotating wheel. Over the past decade, the wayside monitoring of wheel profiles has gained significant importance for monitoring wheel profiles [4,13]. During the wayside inspection, the wayside equipment measures the passing train, resulting in a one-slice measurement strategy [4,6,18]. Typically, during wheel profile inspection (both in-workshop and wayside inspection) the profile is measured only at a specific position of the wheel, the so-called 'one-slice' approach. This 'one-slice' approach is carried out on the basis of the assumption that the wheel profile has the same shape independent of the measurement position along the circumference of the wheel. However, to ensure that reliable information is derived from the measurements, multiple measurements need to be conducted to ensure a reliable representative measure of the wheel profile along the circumference of the wheel. This paper presents a study of the representability of a one-position or one-slice measurement strategy with respect to the wheel parameters from measurements carried out during in-workshop inspection and utilizing wayside monitoring systems to validate the same. The aim of this study is also to improve the possibility of classifying wheels that are in operation with respect to the standard wheel parameters. An improved classification could result in better ride comfort, less wheel and rail wear, and lower maintenance cost for both infrastructure managers and rolling stock owners/operators. The main aspect investigated in this study is the possibility of using single-wheel profile measurements from wayside measurement stations giving one-slice measures of the wheel profile for calculating the standard wheel parameters.

The remainder of this paper is structured as follows. Section 2 introduces the technical background of wheel profiles and standard wheel parameters. Section 3 elaborates the methodology followed for this study. The results and analysis are explained in Section 4, and the conclusions and future work are discussed in Section 5.

2. Wheel Profiles and Wheel Parameters

A railway wheelset consists of an axle fixed to two sets of wheels. For the rolling stock vehicles on the track there are numerous different wheel profiles in use, and the nominal wheel shape is adapted depending on the application concerned [6]. For instance, iron ore wagon wheels used along the Iron Ore Line in Sweden are subjected to large axle loads, and the wheels generally have a profile which provides a larger contact area, thus giving a wider pressure distribution between the wheel and the rail. On the other hand, passenger trains have a particular profile which is crafted to meet the requirements for stability at higher speed. There are also different limitations for the wheel profiles depending on certain factors such as maximum allowed speed, wheel diameter, maximum allowed load, etc. Further, the wheel measures are also controlled by mandatory requirements for high and low thresholds [45].

Figure 1 depicts the wheel profile for a new wheel (marked with a blue line) and a worn wheel (marked with a red dashed line). The wheel profile is commonly divided into two main parts: the flange and the tread. The wheel profile parameters are used to describe the condition of the wheel, and the standard wheel profile parameters are depicted in Figure 1. Flange height (Sh), flange width (Sd), flange slope (qR), and tread hollowing (Th) are the widely established wheel profile parameters in the railway industry and are described below:

- Flange height Sh : vertical distance (in mm) from the nominal running circle (70 mm from the flange back) to the top of the flange
- Flange width Sd : lateral distance (in mm) between the flange back and the flange face measured at a height of 10 mm up from the nominal running circle
- Flange slope qR : lateral distance between the flange face position measured at a height of 10 mm up to 2 mm below the top of the flange
- Tread hollowing: difference in radius between the smallest radius of the tread (close to the running band) and the largest radius close to the field side

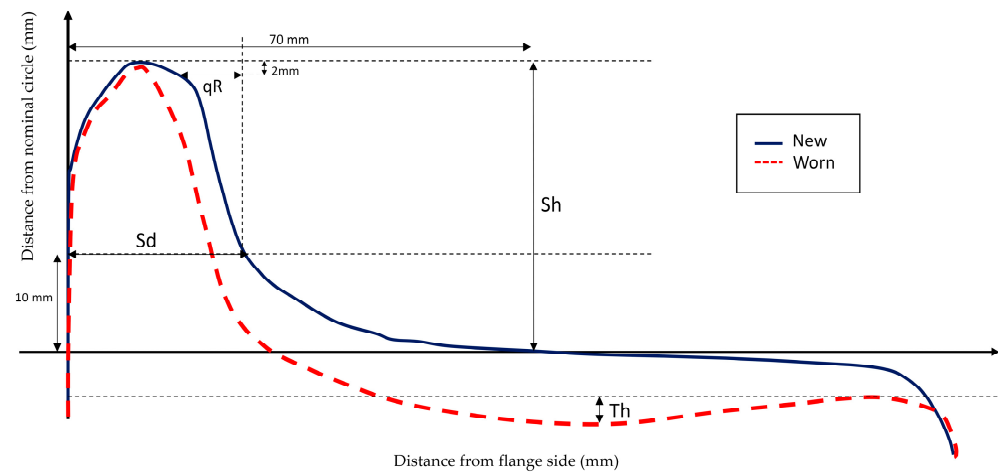


Figure 1. Original and worn wheel profiles, with the wheel profile parameters. qR : flange slope; Sd : flange width; Sh : flange height; Th : tread hollowing.

Measurements of these wheel parameters are essential, as they describe different aspects of the wheel profile and give insights to the status of the wheel with respect to different requirements. For instance, the flange height cannot be too low (to avoid derailment) and cannot be too high (to avoid damages to other track components). Similarly, the flange cannot be too thin (to avoid flange failure and derailments). Measures of these parameters are hence used for maintenance decisions in the railway sector.

In the railway sector, these parameters generally have both maintenance and safety limits, and when some of the measurements pass a high or low threshold of these limits or when a wheel failure occurs, the wheel needs to be reprofiled or replaced accordingly. The intervals between the reprofiling vary significantly depending on the application; for instance, the wheels of lighter trains usually have longer intervals between reprofiling than the wheels of trains with a large axle load.

3. Methodology

This section describes the methodology used in this study. As discussed earlier, the goal of this study is to investigate the representability of a single ‘one-slice measurement’ of a wheel profile carried out during both in-workshop inspection and wayside monitoring. The representability study was carried out for both newly grinded wheels and for wheels with different operating hours. The in-workshop inspection and the wayside monitoring approaches used for this study are briefly described below.

3.1. In-Workshop Measurements

For the manual measurements, wheel profiles were measured along the circumference of the wheel during in-workshop inspections using a handheld measurement system. The measurement system used for this study is a laser-based equipment CALIPRI manufactured by the NEXTSENSE company, Austria. The accuracy of the measurement equipment is $<\pm 80 \mu\text{m}$, and the repeatability is $<\pm 35 \mu\text{m}$. The manual measurements of the wheel were

performed at a workshop owned by the operator of the iron ore traffic in northern Sweden, LKAB Malmtrafik, Sweden.

Seven wheels were measured using the handheld laser-based equipment with a resolution of 35 measurement points equally spaced along the circumference of each of the wheels, giving approximately 100 mm between the measurement points. Table 1 shows the manually measured wheels in the workshop along with the information regarding the age of the wheel in terms of distance travelled in km. Figure 2 depicts the profiles plotted along the circumference of the wheel (HP6448) illustrating the different measurement positions for that wheel.

Table 1. Wheel profiles and their relative age with respect to distance, used for manual measurements.

Wheelset ID	Age (km)	Measurements
HP8628	0	35
HP9270	0	35
HP8507	237,832	35
HP7480	315,740	35
HP6448	317,125	35
HP9264	409,522	35
HP9709	409,522	35

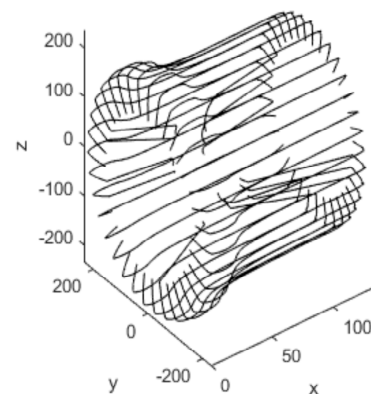


Figure 2. Wheel profiles plotted along the circumference of the wheel using the different measurement positions for the wheel id HP6448.

For the in-workshop measurements, both the reproducibility and the representability of the wheel profile measurements were tested. The reproducibility of the measurements was tested by comparing two operators performing the same measurement task on the same wheel using the same measurement device. The reproducibility was analysed with the wheel profile parameters. The representability was tested for both newly grinded wheels and wheels with different operating hours. For the representability test, measurements carried out by only one of the operators were used. The representability was also analysed with respect to wheel profile parameters.

3.2. Wayside Measurements

Wayside measurements of the wheel profile parameters were performed using a commercial laser-based automatic wheel profile measurement system developed by Beena Vision, USA. The automatic monitoring system is located at the track section situated in the southernmost part of the Iron Ore Line in Sweden. The automatic wheel profile measurement system is depicted in Figure 3, and the system consists of two main units. The first wheel triggers a sensor when a train passes the boxes housing the measurement units and the protective cover opens. The laser beams activate and project laser lines onto the surface of the passing wheels, and the camera captures pictures of this. Each unit consists of two cameras (depicted in Figure 3) and three lasers that produce two images, one for

each flange and tread side of the wheel. The two images are merged to form one image of the wheel profile, from which the wheel profile parameters are estimated (refer Figure 1).

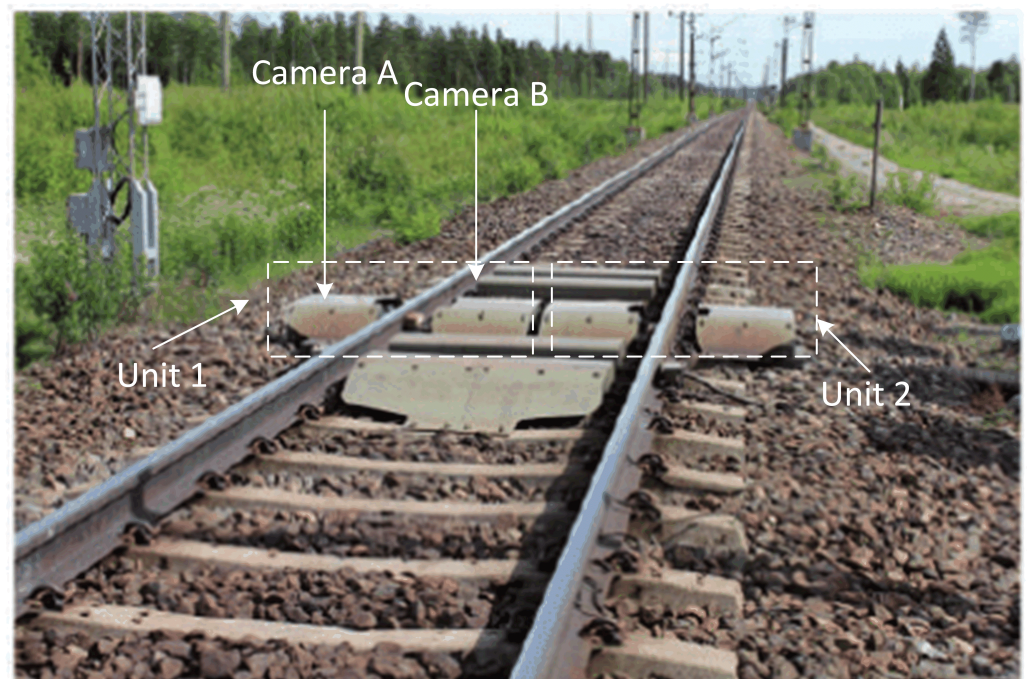


Figure 3. The automatic wheel profile measurement system with its two units located in the southern part of the Iron Ore Line in Sweden.

During the wayside measurement, eight different wheels were measured, and the wheel profile parameters were estimated for each reading. To reduce the effect of wheel wear influencing the study, the wheels were measured during a time span of ten days. During this period, each wheel passed the measurement system ten times, resulting in a set of ten measures for each wheel. Between each measurement, the travel distance of the wheel was approximately 800 km. Depending on the direction of the train, the right or left system was used to measure the wheel profile parameters. Due to measurement errors for some wheels, some measurements had to be discarded. The measurement error involved those sequences where the camera failed to capture and save the images of the wheel. Table 2 depicts the number of measurements recorded for each individual wheel.

Table 2. Number of wheel profile measurements used for each wheel captured using automatic wheel profile measurement system.

Wheel Number	Measurements
Wheel 1	8
Wheel 2	9
Wheel 3	9
Wheel 4	10
Wheel 5	9
Wheel 6	9
Wheel 7	10
Wheel 8	10

4. Results and Discussion

Table 3 depicts the results of the reproducibility measurement where the manual measurement system was tested by two different operators on wheel HP6448. The average value of the mean and the standard deviation for both operators is presented as μ_3 and σ_3 ,

respectively, in the rightmost column. From the table below it is evident that the mean value of all four parameters calculated for the measurements carried out by the two operators was similar, with a standard deviation of 0.6. The repeatability of the handheld equipment is well in accordance with the manufacturer value. For further studies only the measurements carried out by one of the operators were used.

Table 3. Mean values and standard deviations of measured wheel parameters (wheel HP6448) for two different measurement operators.

Parameter	Operator 1		Operator 2		Operator 1 and 2		
	μ_1 (mm)	σ_1 (mm)	μ_2 (mm)	σ_2 (mm)	μ_3 (mm)	σ_3 (mm)	$100 \times 3/\mu_3$
Sh	35.122	0.002996	35.039	0.001409	35.0805	0.00220	0.00628
Sd	26.348	0.001876	26.293	0.002681	26.3205	0.00228	0.00866
qR	11.197	0.000921	11.159	0.000789	11.1780	0.00086	0.00765
Th	1.181	0.000459	1.195	0.000845	1.1880	0.00065	0.05488

Figure 4 depicts the wheel profile measurement performed using the handheld measurement system along the circumference of the wheel HP6448 by one of the operators. The right graph shows a zoomed part of the wheel profile where the difference between the individual measurements is clearly visible.

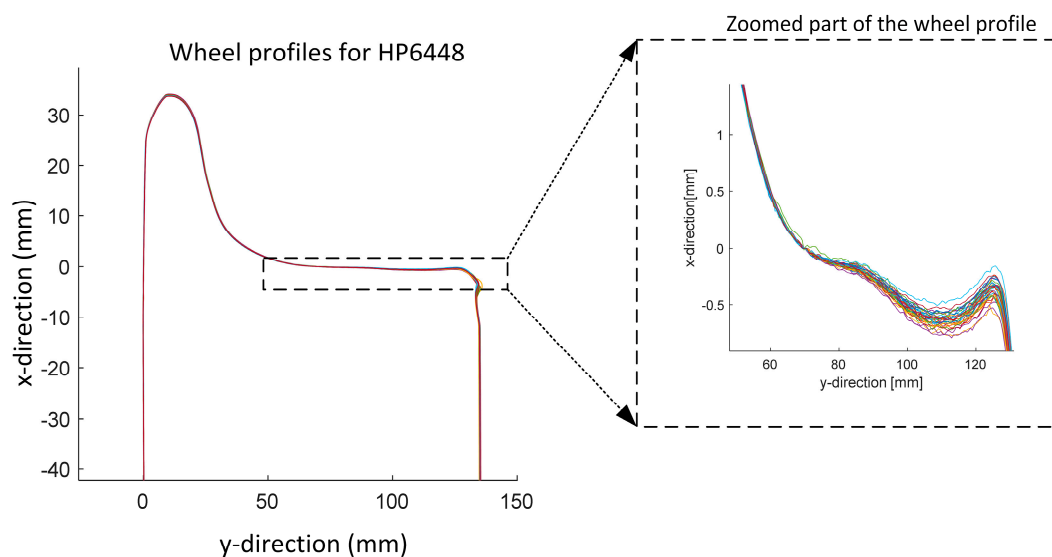


Figure 4. Wheel profile plots of 35 measurements for wheel HP6448.

Figure 5 depicts the box plot, and Table 4 represents the statistical parameters such as mean, standard deviation, and range for the four-wheel parameters estimated for different wheels. Each wheel was measured at 35 different positions along the wheel circumference by the same operator with a gap of 100 mm between each position. The mean value for flange height increased with respect to the running distances of the wheel (running distances of the wheels are depicted in Table 1). Wheel HP9709 with an age of over 400,000 km (running distance) exhibited higher values of flange height, flange slope, and hollow wear than when compared to the relatively new wheel HP8628. The box plot shows that there are variations in all four estimated parameters when measured at different positions within the same wheel. The spread in the parameter was comparatively smaller for relatively newer wheels.

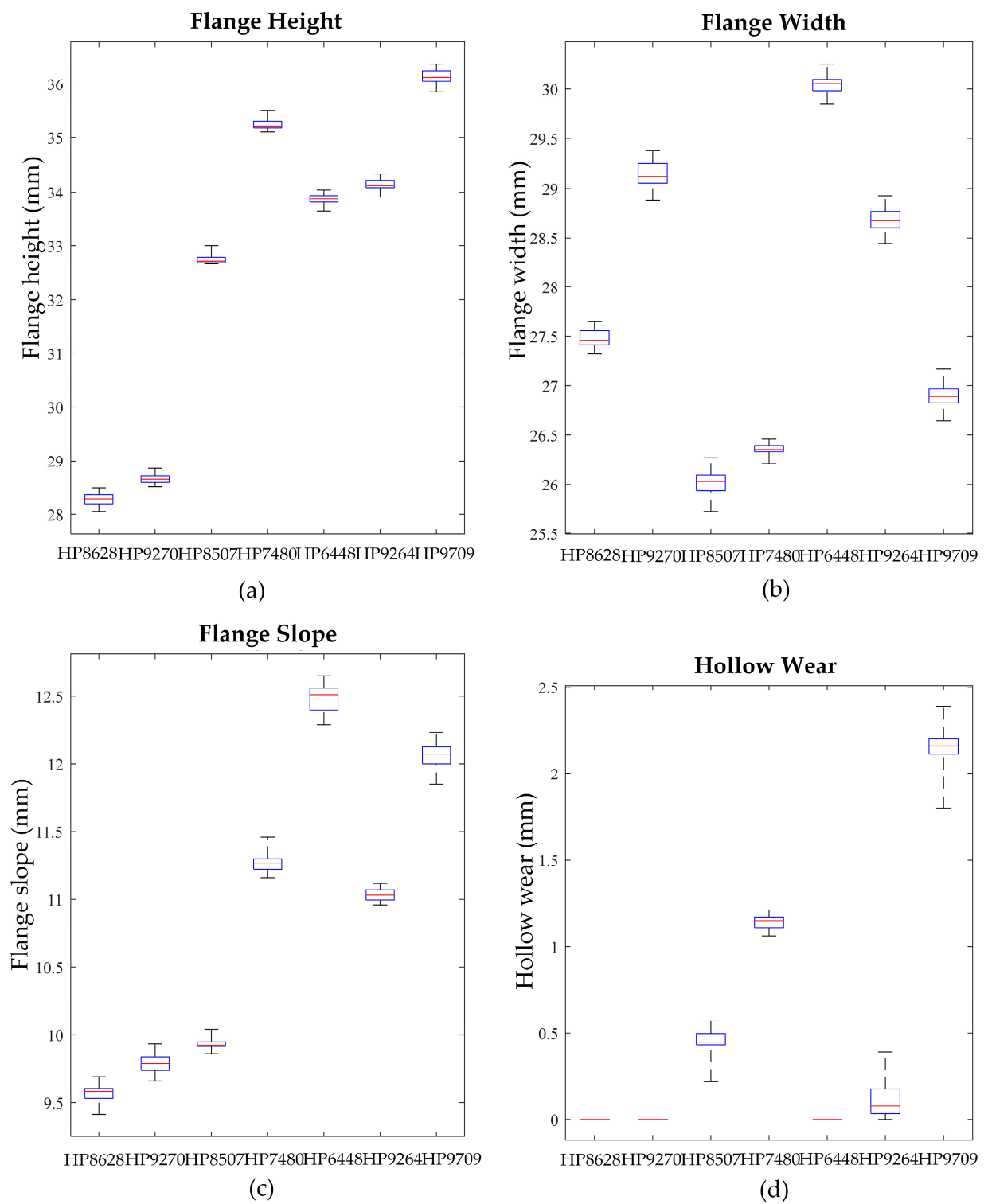


Figure 5. Box plot for the four parameters for different wheels measured using the handheld equipment: (a) flange height, (b) flange width, (c) flange slope, (d) hollow wear. The X-axis for all four plots shows the wheel ID for the studied wheel.

Table 4. Mean, standard deviation, and range of the calculated wheel parameters for different wheels, measured using the handheld equipment. All measurements are in mm.

Wheel Id	Mean (mm)				Standard Deviation (mm)				Range (mm)			
	Sh	Sd	qR	Th	Sh	Sd	qR	Th	Sh	Sd	qR	Th
HP8628	28.283	27.486	9.564	0	0.114	0.091	0.059	0	0.440	0.330	0.280	0
HP9270	28.267	29.142	9.783	0	0.086	0.131	0.0628	0	0.350	0.500	0.270	0
HP8507	32.757	26.013	9.934	0.450	0.085	0.110	0.041	0.067	0.340	0.550	0.180	0.350
HP7480	35.243	26.352	11.267	1.144	0.088	0.057	0.063	0.043	0.440	0.580	0.300	0.400
HP6448	33.867	30.052	12.479	0	0.094	0.093	0.104	0	0.390	0.400	0.360	0
HP9264	34.141	28.684	11.033	0.118	0.100	0.099	0.044	0.102	0.420	0.490	0.160	0.390
HP9709	36.138	26.893	12.065	2.148	0.121	0.121	0.092	0.105	0.510	0.530	0.380	0.590

The highest mean value, standard deviation, and range for flange height (Sh) was observed for wheel HP9709, which had the highest running distance, over four hundred thousand kilometers. The average standard deviation of flange height over all the wheels recorded was 0.1 mm around the mean value, and the average range (difference between maximum and minimum value) was 0.4 mm. The highest mean value for flange width (Sd) was found to be associated with wheel HP6448, and the largest standard deviation for the estimated flange width was found to be for wheel HP9270. The highest range (0.580 mm) for the flange width was observed for wheel HP7480. The average standard deviation for flange width for the measurements across all the wheels in the study was 0.1 mm around their mean value with an average range of 0.48 mm. The highest mean value for flange slope (qR) and the largest standard deviation of the same was associated with wheel HP6448. The range for estimated flange slope was largest for wheel HP9709 with a value of 0.38 mm. The average standard deviation and average range of the estimated flange slope across all the wheels were 0.067 mm and 0.27 mm, respectively. The hollow wear or the tread hollow (Th) was zero for three of the wheels studied (two wheels being new). The highest mean value, standard deviation, and range for hollow wear/tread hollowing (Th) were observed for wheel HP9709, which had the highest running distance among all the wheels observed in this study. The average standard deviation and average range of hollow wear across all the wheels that exhibited hollow wear were observed to be 0.08 mm and 0.4325 mm, respectively. These statistics indicate that there are variations in the estimated wheel parameters for different measurement positions within the same wheel.

Figure 6 depicts a histogram plot of flange height measured for eight different wheels. The highest average mean flange height value was associated with wheel 1 (measured 8 times). The largest standard deviation around the mean value (0.517 mm) and the largest range (1.44 mm) for the flange height was found to be for wheel 2. The average standard deviation across all the wheels for the estimated flange height was 0.422 mm, and the average range was 1.07 mm. The average standard deviation of flange height estimated using the wayside measurements was over four times higher than when using the handheld equipment, and the average range was over two times.

Figure 7 depicts the histogram plot of the flange width measured for eight different wheels. The highest mean value for the flange width was observed for wheel 2 with a value of 29.88 mm. The largest standard deviation around the mean value (1.028 mm) and the largest range (3.33 mm) for the estimated flange width was found to be for wheel 1. From the histogram plot, the spread in the flange width values is quite significant. The average standard deviation across all the wheels for the estimated flange width was 0.815 mm, and the average range was 2.5 mm. The average standard deviation of flange width estimated using the wayside measurements was over eight times higher than when using the handheld equipment, and the average range was over five times.

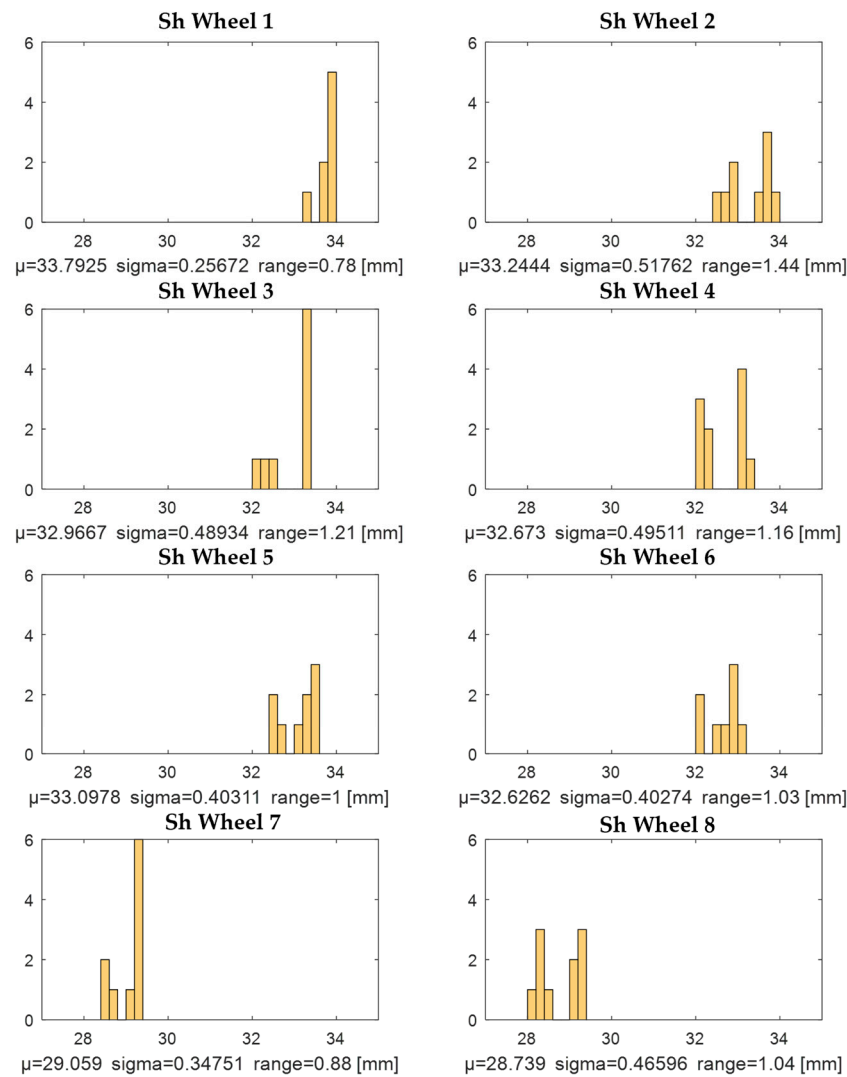


Figure 6. Histogram of flange height (Sh) for eight different wheels measured by the wayside wheel profile measurement system. X-axis represents the flange height in mm and Y-axis represents the number of measurements recorded. The mean, standard deviation, and range of the measurements for each wheel are described below the plot.

Figure 8 depicts the histogram plot of the flange slope measured for eight different wheels. The highest mean value for the flange slope was observed for wheel 6 with a value of 11.887 mm. The largest standard deviation around the mean value (0.656 mm) and the largest range (1.9 mm) for the estimated flange slope was found to be for wheel 2. The average standard deviation across all wheels for the estimated flange slope was 0.397 mm and the average range for the same was 1.1 mm. The average standard deviation of flange slope estimated using the wayside measurements was around six times higher than when using the handheld equipment and the average range was over four times for the same.

Figure 9 depicts the histogram plot of the tread hollow measured for eight different wheels. Wheels 6, 7, and 8 did not have any hollow wear recorded from over eight or more measurements for each wheel. For wheels 1 to 5, the highest mean value for the tread hollow was observed for wheel 5, with a value of 1.5 mm. The largest standard deviation around the mean value (0.145 mm) and the largest range (0.4 mm) for the estimated flange slope was found to be for wheel 4. The average standard deviation across the five wheels that exhibited hollow wear was 0.106 mm, and the average range for the same was 0.28 mm. The average standard deviation of hollow wear estimated using the wayside measurements

was around one and half times higher than when using the handheld equipment, and the average range was similar for both cases.

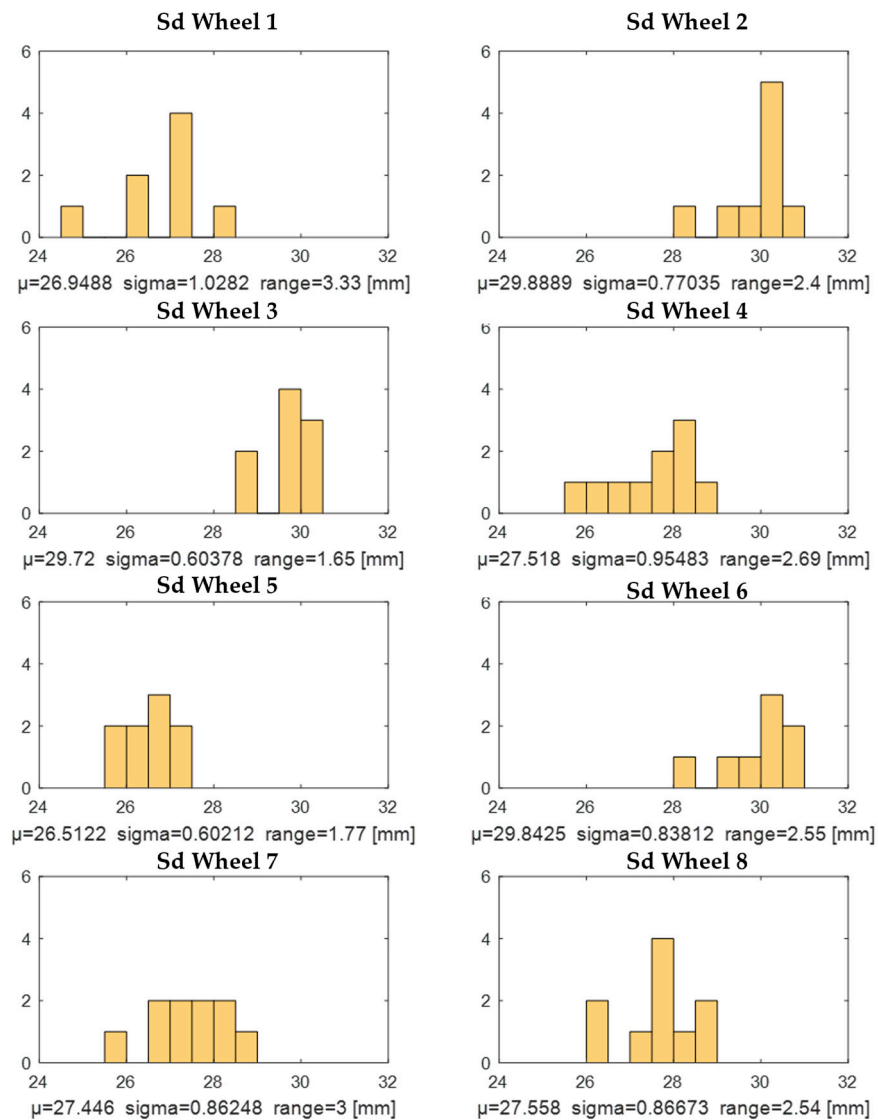


Figure 7. Histogram of flange width (Sd) for eight different wheels measured by the wayside wheel profile measurement system. X-axis represents the flange width in mm, and Y-axis represents the number of measurements recorded. The mean, standard deviation, and range of the measurements for each wheel are described below the plot.

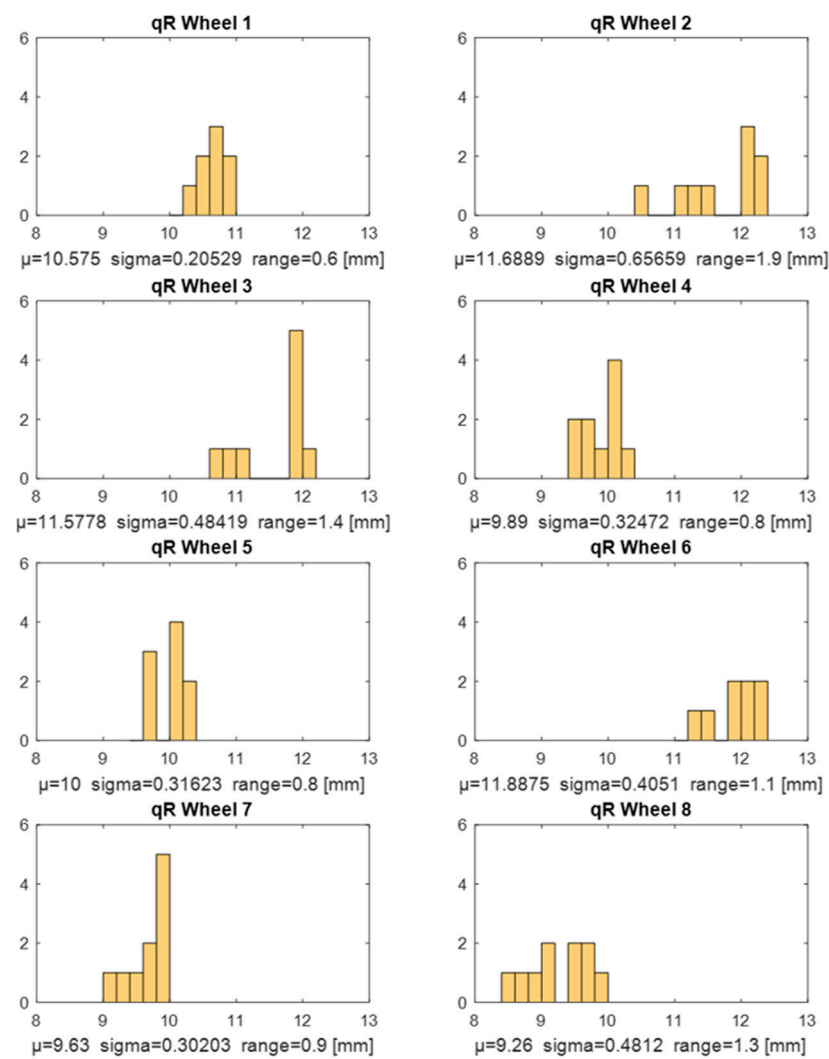


Figure 8. Histogram of flange slope (qR) for eight different wheels measured by the wayside wheel profile measurement system. X-axis represents the flange slope in mm, and Y-axis represents the number of measurements recorded. The mean, standard deviation, and range of the measurements for each wheel are described below the plot.

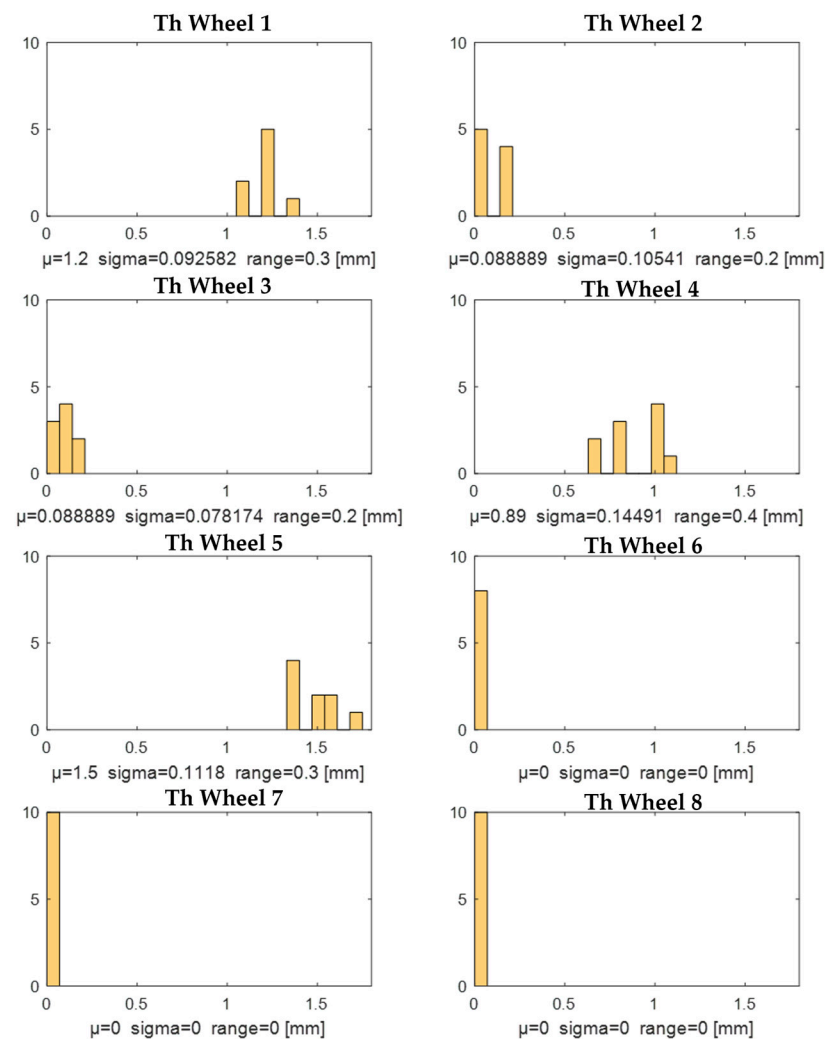


Figure 9. Histogram of Tread Hollow (Th) for eight different wheels measured by the wayside wheel profile measurement system. X-axis represents the tread hollow in mm, and Y-axis represents the number of measurements recorded. The mean, standard deviation, and range of the measurements for each wheel are described below the plot.

5. Conclusions

Rail wheels are crucial components in the railway infrastructure that need to be periodically monitored to ensure safe and reliable operation. The goal of this study was to investigate the representability of a one-slice measurement strategy for railway wheel profiles with respect to wheel profile parameters. Four wheel parameters were estimated on the basis of the measurements recorded: flange height (Sh), flange width (Sd), flange slope (qR), and tread hollow (Th). There were variations in all the estimated parameters for different positions measured within the same wheel, indicating the spread of wheel profile parameters along the circumference of the wheel. In order to exclude the dependency of the measurement operator, the results of the two operators were compared and the difference between the operator dependency was low compared to the studied effect of the position along the circumference. As an initial validation of the results, measurements from a wayside monitoring system were investigated in order to see if a similar spread was visible for multiple measurements.

On comparing the calculated range of standard deviation of the parameters estimated from measurements using handheld equipment to the same parameters measured by wayside measurement equipment, it can be concluded that the wayside measurements show a larger spread along the circumference of the wheel. A similar spread from both the

measurements was observed only for the hollow-wear parameter. Based on the wheels analysed in this study, the one-slice measurement strategy of a wayside wheel profile measurement system may not be adequate to estimate the wheel profile parameters for condition monitoring purposes. Multiple measurements are required to represent the parameters along the circumference of the wheel for reliable condition monitoring of the wheels. Future studies will investigate the one-slice measurement strategy from the wayside measurement system to estimate high-level parameters such as the equivalent conicity of the wheel. This study was carried out only on wheels of a particular wagon type (iron ore wagon); future studies will focus also on wheels of other wagon types including high-speed and passenger trains. In addition, the future studies will examine the evolution of the spread in wheel profile parameters with respect to wheel age.

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Conflicts of Interest: The authors declare no conflict of interest.

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