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Using Data from Multiple Wayside Train Monitoring Systems to Detect and Estimate the Size of Wheel Flats on Railway Vehicles

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ABSTRACT

The aim of this paper is to propose a method for detecting the occurrence of wheel flats and estimating their size from data of multiple wayside train monitoring systems during normal operation. Thereby, the need for manual inspections can be reduced or at least becomes more efficient, releasing resources to focus on other aspects in maintenance. Moreover, decision making on wheel set exchanges and wagon shunting is improved and the risk for human-errors is reduced.

The detection of wheel flats exploits the fact that wheel flats usually occur on both wheels of a wheel set at the same time rendering a jump in the recorded force values by wheel impact load detectors. The wheel flat length estimation does not realy on a statis mapping of recorded forces to length value, but instead uses a model-based approach where the passage of a damages wheel over a wheel impact load detector is simulated using a concentrated parameter dynamic model for the vehicle and measurements for passage speeds and wagon load.

The scheme is exemplified on a numerical example providing reasonable outcomes compared to previous literature. It was further evaluated using some real-life examples where ground truth data from workshop assessments were available. The outcomes are encouraging and further validation in a field test is recommended.

Keywords

Wheel flats, wayside train monitoring systems, dynamic vehicle model, detection, length estimation

1 INTRODUCTION

Predictive maintenance of railway vehicles can improve the reliability and safety of train operations while optimizing the cost for maintenance. Actionable insights on future asset conditions are usually provided to the users for their planning of maintenance efforts to enable proper decision making . Getting access to characterisations and evolutions of wheel damages while the asset is in operation and without manual intervention further increases operational efficiency by enabling better informed decisions.

Wheel flat or Out of round wheels in railway operation do not only jeopardize the transport of a specific good to reach its destination, but also the infrastructure that the train operates on. Consequently, there are both regulations and practices in place which should both protect the infrastructure and the rolling stock, like e.g. the General Contract of Use (GCU) [1] and the technical regulations in place in Sweden [2]. According to the GCU, wheel flats of 60 mm and larger in length are not admissible for operation.

It is well known that wheel flats induce large wheel-rail contact forces [3, 4, 5] increasing with the size of the wheel flat, which can be measured by wheel impact load detectors (WILD). Thus, WILD detectors can be used to identify wheels with damages and if the measured forces exceed predefined thresholds to take them out of operation. The open question is which forces are associated with a certain wheel flat length. The aim of this paper is to propose a method to identify wheel flat as damage category and subsequently determine the length of the flat. The value of knowing the flat length apparent as it provides insights on the operational fitness of a wagon.

In previous research, there is a consensus that the wheel to rail impact forces due to wheel defects are dependent on train speed. This has been shown in studies based on actual field test as well as simulations of theoretical models [5, 6]. However, speed is not the only factor that influences the impact load. In [4] it was claimed that the shape and size of the wheel defects, axle load, train speed, and contact patch stiffness are factors that influence impact loads the most, which is more or less confirmed according to [3].

Understanding how the force and wheel flat length relationship is

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affected by different factors has been an active field of investigation. In [7] impact loads from wheel flats as a function of train speed in the interval 30-100 km/h are investigated ad show a slight increase in peak impact force with increased speed for short (25-40 mm) and long (75-100 mm) wheel flats. In [6] it is shown that, for all wheel flat lengths, the increase in impact force slows down at speeds over 80 km/h. Further a model for the relationship is derived. A more sophisticated approach that uses on-board sensors and uses an explicit dynamic vehicle model is proposed in [8], which is also the base of this paper. Further approaches are discussed in [9].

Due lateral motion of a wagon and the contact patch along the track, a detector might not measure the full extend of a wheel flat, which is why multiple WILD detector measurements need to be combined to eventually the wheel flat in its completeness. Fusing multiple detector passage poses its own challenges as discussed in [10, 11]. Another challenge is the access and the management of the data aligned with the wheel in question, which has been solved in [12]. The same platform will also be used to implement the proposed method.

The paper is organized as follows. First analytics approach is summarized and the WILD detectors are introduced. Thereafter the methods to detect wheel flat and to estimate the length of the flat are discussed. It is then followed by the test and validation of the proposed analytics approach. The paper ends with some conclusions and recommendations for future work.

2 APPROACH OVERVIEW

The detection wheel flat and subsequent estimation of its length builds on the notion that a wheel flat generally occurs on both wheels of a wheel set at the same time, leading to a substantial increase of f_{dyn}.

The detection of the wheel flat then encompasses three steps:

1. Track the dynamic force over time for left and right wheel
2. Establish a lower bound as the “normal” force level for each wheel and track it over time
3. Detect the occurrence of a simultaneous jump in the force levels on both left and right wheel
4. Flag for a wheel flat after the occurrence of the jump

When a wheel flat is flagged, the length of the wheel flat can be estimated for each wheel individually. The idea is that the recorded dynamic force f_{dyn} is relating to the length of the flat. Then a reverse calculation from the force to the wheel flat length in line with [8] will be estimated as follows:

1. Represent the wagon as a partial car model using a concentrated parameter system
2. Simulate the dynamic force during a passage of the wheel over the detector with different individual flat lengths
3. Select the flat length which fits the recorded dynamic force best.
4. Redo the estimate after the next passage to update the flat length and keep the largest estimate as the new estimate.

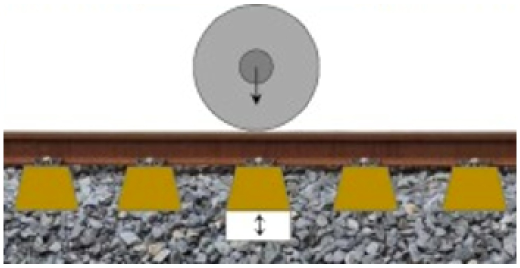

Figure 1: Sketch of a wheel passing over a wheel impact load detector, indicating potential movements of the sleeper in the ballast.

To correctly estimate the flat length, the wheel flat need to overlap in its entirety with the contact patch of the wheel-rail contact during the passage over the WILD.For this reason, the estimate need to be redone. It also means that the approach underestimates the flat length but over time (subsequent WILD passage) will converge to the correct flat length.

The approach has certain limitations. One-sided flats will not be detected, those can occur in uneven load scenarios or when a stumbling block is not correctly used. Moreover, multiple damages and especially RCF damages may occlude the presence of a wheel flat.

3 WHEEL IMPACT LOAD DETECTOR

Detecting wheel damages on a wheel using a wayside train monitoring system can be accomplished by measuring the contact forces between the wheel and rail, as so called wheel impact load detector (WILD). Assuming that the rail is in perfect condition at the monitoring site, high force values would reflect certain damages on the wheel.

In Fig. 1, the wheel-rail contact is depicted. The yellow sleepers are equipped with measurement devices for forces on the rail. Clearly, potential weight induced motion of the sleepers will affect the measurement of forces negatively. It is therefore important to ensure a proper installation and maintenance of the sleepers and ballast at the measurement site, to reduce systematic measurement errors.

To measure the wheel along its circumference one measurement device at one sleeper is insufficient. Therefore, the complete WTMS is composed of multiple measurement devices which are placed out along the track, as can be seen in Fig. 2. An additional factor is the lateral motion of the wheel which means that a local damage on the running surface of the wheel may not or only partially in contact with the rail. Clearly, the number of measurement devices affects both cost and quality of the detection of damages .

For the passage of a wheel over the WILD reports three forces, mean force, peak force, and dynamic force. In Fig. 3, it is exemplified how the forces evolved during the passage, when there is one isolated damage on the wheel’s running surface. Essentially, the dynamic force is a simple subtraction of the peak and mean force as

Figure 2: Picture of a wheel impact load detector installation, where the individual measurement devices are shown in yellow.

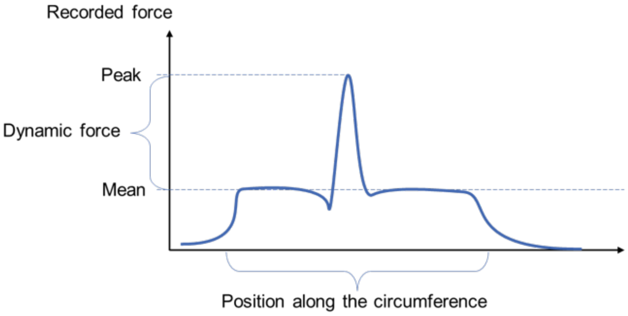

Figure 3: Sketch of the forces reported by a WILD for the wheel-rail contact along the circumference for a wheel with one individual damage.

$$f_{dyn} = f_{peak} - f_{mean} \tag{1}$$

In (1), the mean force f_{mean} can be interpreted as an approximation of the force induced by the weight of the vehicle. Ideally, if there are no damages on the wheel, the peak force f_{peak} should equal f_{mean}, thus $f_{dyn} = 0$.

4 WHEEL FLAT DETECTION

Before estimating the wheel flat length, it has to be established that the recorded force data originates from a wheel flat. Thus, classifying the damage as wheel flat or not.

The main idea is to use the fact that a wheel flat is an instantaneous event rather than a gradual change and usually occurs on both wheels of a wheel set at the same time. There are cases where this is not true, but it remains to be seen in a larger field test how often this assumption does not hold. The approach to detect a wheel flat is therefore to identify a sudden force increase simultaneously on both sides of the wheelset.

A sudden occurrence of a wheel flat would then render a positive outlier in the force data when compared with a historic window of pre-defined size and a lag to the latest measurement. The historic window of force data is then used to establish a mean and variance of the data and the sudden force increase need to exceed a threshold that depends on the variance of the historic data. The historic window of data points is then moving along with the data and then including the sudden raise in force, which prevents renewed detection flags.

The detection is then taking place as follows:

- The measurement value gets a z score based on the mean value and standard deviation of the historic window.
- If the z score is more than set threshold and the sum of the z scores it more than the sum threshold, then the measurement is said to be a sudden rise or jump.
- If the rise is detected, the wheelset becomes a candidate to be classified as a wheel flat.
- Since it is not uncommon to get outliers in the force data, it is required to have two subsequent jumps, i.e. fulfill the aforementioned requirements on the z scores, before the wheelset gets classified as a wheel flat.

The lag of the historic window makes sure that first elevated force values are not included in the historic window when the second measurement after the wheel flat event is up for decision by the algorithm.

Using data and ground truth information from the field, the threshold on the z score and sum of z scores can be trained for a specific performance criteria which should render few false positive detections.

5 FLAT LENGTH ESTIMATION

The flat length estimation is to a large extent making use of the methodology that is proposed in [8]. The approach is intended for the use with on-board sensors that are mounted on the axle boxes. Here, we intend to apply a modified version on data from wayside trains monitoring systems, namely wheel impact load detectors.

Instead of trying to map a recorded force to a damage length, which has reported shortcomings [3], the idea is to simulate the passage of a wheel over the detector having a wheel flat of arbitrary length. The simulation is then reproducing the forces that are recorded by the detector, and in that way to determine the most appropriate wheel flat length.

5.1 Simulation of a passage

The origin for the increased forces during a wheel passage over a detector is the change in the wheel radius at the wheel flat, which is depicted in Fig. 4. There it can be seen that the are two versions of a flat, a freshly generated one and one that is softened at the edges (rolled-out). The roll-out occurs quite directly after the flat has been generated [8].

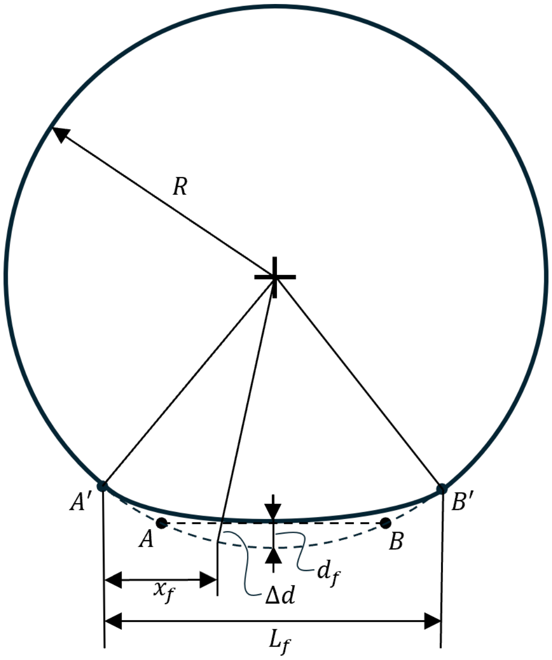

Figure 4: Sketch of a wheel flat for fresh (dashed) and worn (solid) condition and their geometry

The radius variation is given by

$$\Delta d = \frac{1}{2} d_f \left[1 - \cos \frac{2\pi x_f}{L_f} \right] \tag{2}$$

with

$$d_f = \frac{L_f^2}{16R} \tag{3}$$

In a simulation, the radius variation (2) is the input signal during a wheel rotation. For the simulation a dynamic vehicle model is used which is depicted in Fig. 5. The vehicle dynamics model is a concentrated parameter model of an eight of the vehicle reflecting the different components in the vehicle. The model can then be represented by a differential equation that is given in Fig. 6

A remaining unknown is the stiffness of the rail-wheel contact. According to [13], the contact stiffness can be modeled by (11) in the article. There, f_2 is replaced by the static load during the passage to calculate k_w and will be used in the simulation of the passage.

The simulation will then use the recorded mean force f_{mean} as an approximation of the load and the recorded passage speed. All remaining parameters are known.

The simulation will then render the forces that can be observed and most noteably the dynamic force f_{dyn}. The maximum positive value of the simulated dynamic force is then the dynamic force reported by the WILD detector.

5.2 Optimizing for the flat length

The wheel flat length is the property that we try to estimate. As simulation uses the flat length as an input variable, an iteration over wheel flat lengths from 10 mm to 100 mm is used to optimize for the most appropriate wheel flat length.

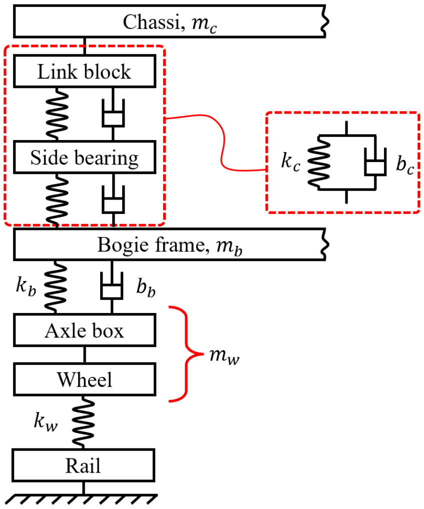

Figure 5: Sketch of the simplified vehicle model for the simulation of the dynamic forces during the passage over a detector.

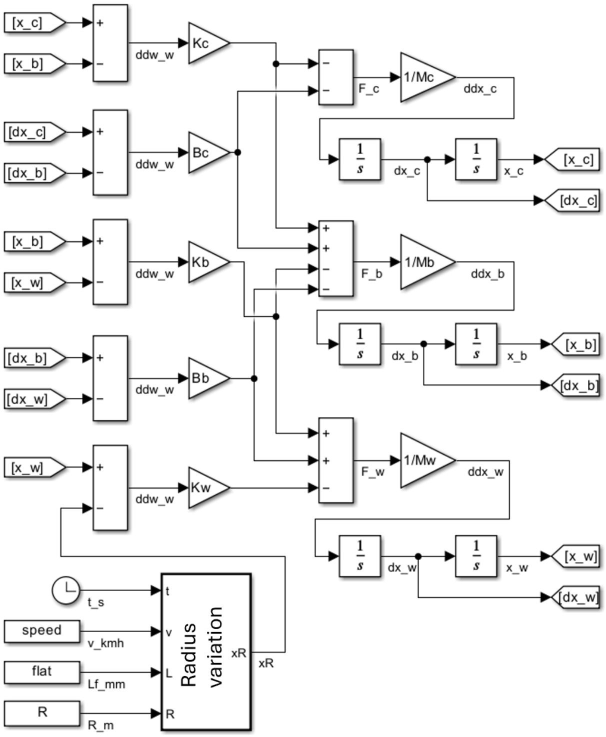

Figure 6: Blockdiagram of the simulation model for the simulation of the dynamic forces during the passage over a detector.

Table 1: Wagon parameters used for the simulations

Parameter	Value	Unit
m_c	7519.5	kg
k_c	$50 \cdot 10^6$	N/m
b_c	$140 \cdot 10^4$	Ns/m
m_b	518	kg
k_b	$1354 \cdot 10^3$	N/m
b_b	$140 \cdot 10^4$	Ns/m
m_w	712.5	kg

Since the resolution of the wheel flat length is sufficient with 5 mm, 21 simulation steps need to be performed at most. Alternatively, a lookup table can be generated where passage speed, load, and wheel flat length are iterated. The optimization then reduces to a table lookup.

5.3 Some considerations

The wheel flat length estimation depends on quite many factors and parameters. While the parameters can be uncertain, like the stiffness constants, the damper constants and the masses and induced errors, factors like ambient and wheel temperature and overlap of the wheel flat with the contact patch during the passage of the detector might have a larger impact.

The ambient and wheel temperature have an effect on the tensile strength of the steel. In the railway literature there is little information regarding these effects, but in the construction area some information is found. In [14], a model for the E-modulus depending on the temperature is proposed. Evaluating the model for the typical temperature ranges that the rail and wheel are exposed to shows that according to (17), the effect can be neglected.

When it comes to the overlap of the contact patch during the detector passage and the wheel flat, the detector might measure a wheel flat which is smaller in length than the real extend. As a result the matching between recorded dynamic force and the simulation can lead to a smaller estimate.

Therefore, the estimated wheel flat size has to be treated as a underestimated value which can increase for subsequent passages and associated estimates. Assuming the wheel flat will not change in size and no new additional flat of larger size occurs, the maximum of current and all prior estimates is the most appropriate estimate of the size.

6 TEST AND VALIDATION

The aim of this paper was to propose a new method for the detection and length estimation of wheel flats. As such the test and validation will refrain from performing a large field test. A field test is planned and the outcomes will be reported in future work.

Here, the focus will be to discuss a numerical exmaple, the implementation of the method in a cloud-based SaaS solution according to [12], and a limited real-life case.

6.1 Numerical example

For the numerical example, parameters of a real life wagon with a Y25 bogie constellation will be used. The parameters for the wagon are given in Table 1. The weight m_c of the chassis also includes a load on the wagon, as it exceeds the tare of the wagon.

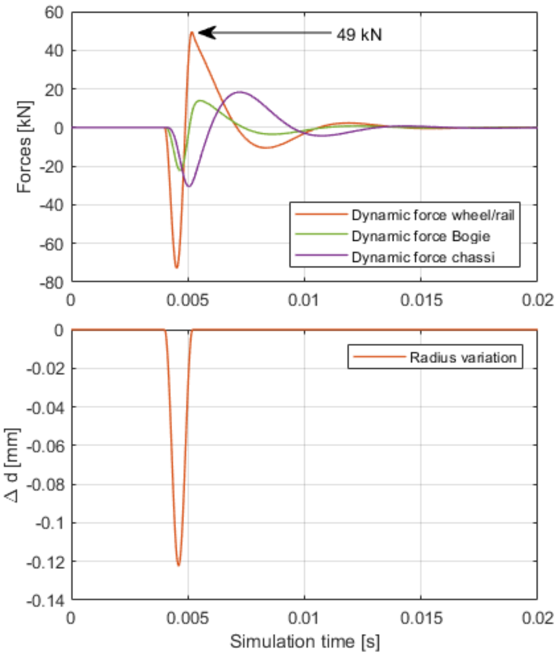

Figure 7: Example of the dynamic forcse for a wheel flat length of30 mm observed during a passage over a WILD.

The simulation makes use of the block diagram shown in Fig. 6 which is a representation of a 6^{th} order continuous-time differential equation. The simulation is now conducted for a speed of 90 km/h and a wheel flat length of 30 mm. The parameter k_w is calculated as indicated in section 5.1. In Fig. 7, the radius variation and the resulting dynamic forces on the rail-wheel contact, the bogie and the chassis are shown. It can be seen that the wheel-rail contact reaches a peak in the dynamic force, which is the expected dynamic force reported by the WILD.

Thus, for the model parameters, load, speed, and wheel flat length the expected dynamic force is 49 kN. Conversely, for the given scenario the wheel flat length can be determined on the basis of the reported dynamic force. Note, a perfect overlap between the contact patch and the wheel flat is assumed.

Assuming the model parameters and wagon load are constant, simulations for varying speed and wheel flat length can be conducted. For each combination of v, L_f the maximum value of the dynamic wheel-rail contact force f_{dyn} can be recorded. The surface $f_{dyn}(v, L_f)$ is depicted in Fig. 8.

6.2 Implementation

The implementation of the method in a cloud-based environment can be achieved in two ways: (i) as soon as a wheel flat is detected, the passage data is used to simulate f_{dyn} for all possible wheel flat lengths; (ii) a look-up table is pre-calculated for all possible wheel flats, speeds, and loads.

Since the latter reduces the amount for processing over time and

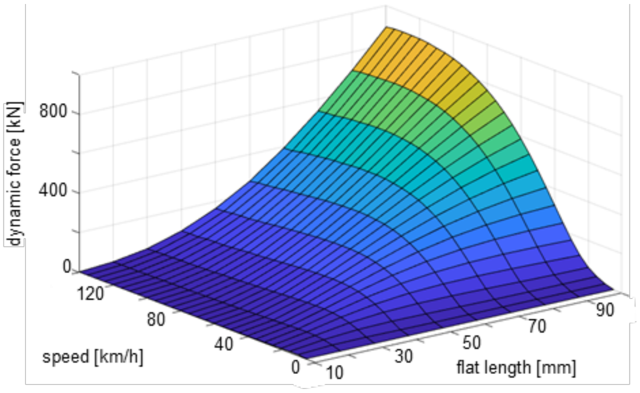

Figure 8: Example of a dynamic force surface depending on passage speed and wheel flat length, assuming a constant load scenario.

only a table look-up is needed, this is the preferred approach. In order to pre-calculate the loo-up table the differential equation is discretized and the variable range and resolution is determined. In the simulation of the model in Fig. 5, wheel flat lengths values ranging from 10 to 100 millimeters with a 5 mm resolution and speeds ranging from 0 to 140 km/h with a 5 km/h resolution, and loads ranging from 0 to 12500 kg with a 500 kg resolution are used. For each simulation, the largest recorded wheel-rail contact force is saved. A lookup table is then created where for each tuple $v, f_{dyn}, m_c + m_b + m_w$ that was simulated, the corresponding wheel flat value can be found.

When estimating the length of the wheel flat, a call for this lookup table is performed. By searching after the dynamic force -speed pair that is most alike the one recorded, we can return an approximation of the wheel flat which would have resulted in the dynamic force which was recorded.

6.3 Evaluation using real-life cases

To evaluate the WFD and FLE feature, wagons equipped with Y25 bogies passing WILD wayside detectors on a regular basis were required. In addition, the validation requires ground truth information about flat length, typically measured by a maintainers upon wheel set exchanges in the workshop.

Due to data availability reasons, freight fleets operating in UK, Netherlands and Sweden are targeted. UK is included in the initial evaluation despite the fact that they operate on a TF25 bogie which is though similar to the Y25 in overall design but still is a different bogie type.

For these three regions, WILD data is acquired and processed continuously from the infrastructure owners, and since the WILD network is sufficiently spread out, flats can be identified close to their origin and become measured at the next endpoint of the transport. The initial evaluation focuses on identifying clear and extensive flats on wagons in operation, that can be assessed and measured before entering operation again.

6.4 Outcome

Initial evaluation cases showed varying but promising results. The WFD feature identified mostly clear wheel flats, which were obvious in both data and during ocular assessment. Some damages, such as sliding damages, replicating the behavior modeled for a wheel flat were also highlighted.

Figure 9: Example of wheel damages and how those can be assessed using magnetic rulers and photos.

Looking at FLE, the precision varied from near spot on estimates to largely deviating ones. In Fig. 9, some examples for damages where a clear wheel flat can be observed in the left image, while more obscure and difficult cases are shown in the middle and right. Given the identified limitations, it is clear that not all wheel flats would yield an accurate estimate.

However, it is worth highlighting the fact that these precision results assumes that the ocular estimation is the ground truth. The initial evaluation cases also makes it clear that the task to judge the length of a flat in millimeters by visual inspection, is a complex task for a human. An ambiguity in this task is the uncertainty where the starting point and endpoint of the flat is.

Due to this, the ground truth information is partly dependent on the person doing the measurement and their interpretation. In the initial results it also becomes clear that the WFD do not only detect individual flats but also damages more similar to sliding damages (material built-up) and flats with multiple flat spots in a row.

The FLE feature obviously struggles to estimate the length of these due to the assumption that flats are more geometrically perfect, as highlighted in Fig. 4. The initial tests show similar results for all three fleets.

A more formal assessment of field tests to quantify performance metrics and cause for misjudgment need to be conducted.

7 CONCLUSIONS

In this paper, a novel method for the detection of wheel flats and the estimation of their length using multiple WILD data is presented and discussed. The methods is a modified version of a method that was proposed for on-board sensing systems.

The detection of the wheel flats is based on the notion of simultaneous jumps in the dynamic force from WILD data, while the method for the length estimation makes use of the vehicle dynamics and data from multiple detector passages to provide a consolidated estimation of the length by matching the simulation of a passage with the recorded data.

The methods are assessed both in simulation and using real-life data from a number of cases. The results indicate that the detection and estimation schemes provide correct outcomes that can be used in decision support for maintenance decision on wagon wheel sets. Namely, the flat length estimation was within $5\ mm$ of the actual wheel flats assessed in a workshop.

It is recommended to validate the proposed scheme in a larger field test to quantify the performance and understand the limitations of the approach.

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