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Detector response from a defective wheel

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ABSTRACT

This paper deals with field validation of the force response from a defective wheel after normal service. The defective wheel represents a typical defect arising from normal winter operation in a cold climate. The current detector is a typical wheel load impact detector that has been in use for about fifteen years; this type of detector is widely used in the infrastructure. The wheel has defects of up to1.8 mm in depth and an un-roundness of 0.2 mm. The results from this investigation, pertaining to the particular vehicle and wheel defect, show a linear correlation of speed and force response. Each change in speed of 1 km/h changes the force response by about 0.9 kN.

1. Introduction

To meet the requirement of high capacity on a track, parameters such as high availability and reliability also need to be met. Early warnings of degradation and defects from the rolling stock and the infrastructure have to be a part of the information base regarding actions that need to be taken to enhance the capacity on a track. The monitoring system indicates problems at an early stage in order to maintain a high level of service by the railway system. This also means that the alarms and warnings from condition monitoring systems need to be consistent. In modern railway infrastructure, different types of condition-monitoring systems are installed to ensure a high level of safety and to keep the operational capacity of the track available. Condition monitoring systems are divided into two main categories: on-board monitoring systems and wayside monitoring systems. The purposes of having wayside monitoring systems are to keep track of the vehicles, be able to take action before safety issues appear, and to be able to remove harmful wheels from the track before the wheel degrades the track and track components. Types and parameters that can be measured with wayside monitoring systems are discussed in the review by Barke [1]. Monitoring systems, in other words, provide a high level of safety on the track, and also enhance track availability and capacity. This in turn reduces train delays in general, as well as unexpected failures of the infrastructure that degrade the track and its components. Other advantages of these systems are the ability to find and correct defects, thus keeping the track and vehicle-operation costs low.

As an example, for the Swedish infrastructure network, the delay time of trains due to wheel defects in 2018 was 1588 h, which was one of the largest causes for delay according to error codes. This impacted the availability of both the track and the vehicles. After an event, the track needs to be inspected, which affects capacity on it. The vehicle also needs to be inspected, and a decision needs to be made as to whether the vehicle can operate with or without limitations, such as speed restrictions. In other words, lots of problems are associated with wheel defects, and these in turn affect the entire railway network, with costs to the end-user and to society.

The research in the field of wheel out-of-roundness has expanded significantly since the 2000s and is expected to continue growing. Examples from this period include the works of Nielsen [2,3] and Barke [4], which provide comprehensive insights into the field. Additionally, research has been conducted on noise and vibrations resulting from wheel-rail impact loads [5], high-speed applications have been explored through finite element simulations that illustrate the development of out-of-roundness [6,7] and root case analysis for wheel tread polygonization [8]. This research primarily focuses on the wayside monitoring station and its relationship with force responses resulting from train speed.

Wayside monitoring systems, also called vehicle check-points, are used to monitor the rolling stock. Some examples of wayside monitoring systems are wheel impact load detectors (WILD) [9], wheel profile measurement systems [10], and other types, such as hot wheel and hot box measurements [11]. Research has also been done on wayside monitoring systems to support maintenance decisions [12]. There is also a risk of rail breaks with high wheel force; nevertheless, the defects on

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rail need to be of a certain length before a rail break occurs under regular traffic [13]. The theoretical investigations of this detector and a methodology for predicting the probability of an instant rail break was performed. The article mentioned focuses on the rail foot crack by a prescribed distribution of dynamic wheel loads related to the traffic on a heavy haul line [13]. The latest summary of out-of-roundness of railway wheels give a comprehensive description of the field [14].

However, little of the published research deals with equipment that is in service for commercial use, nor does it describe how a variation in speed affects the results in the monitoring of the wheel. Hence, this investigation will look into the force response of a defective wheel from a WILD in service. The defective wheel comes from a regular operation and had been captured with high alarm due to the wheel defect. The selected WILD is one in regular service that represents well the WILDs that are located in the infrastructure. This type of WILD is built of load cells for measurement of rail seat loads on a number of sleepers; there are also other types of technologies, such as fibre optic sensing for measurement of rail bending movement. Both of these are in use in the railway infrastructure in Sweden. The questions to be answered are: what is the relation of speed and measured force response for a WILD, and is the relation linear or non-linear in the range of 10–100 km/h? The goal for this work is to be able to predict the new speed for a train that has been stopped for high force, just over the threshold, from a WILD. For instance, if the train exceeds the threshold with 5 kN, how much speed reduction is needed to stay below the threshold with some safety margin? This train is in northern Sweden, located at the southern loop of the Iron Ore Line close to the city of Luleå.

This work was conducted in collaboration between the owner of the rolling stock and the manager of the infrastructure.

The paper is structured as follows.

- Description of the track and WILD (section The infrastructure and Wheel Impact Load Detector)
- Overview of Wheels and Specific Wheel Damages (section Wheel Defects in General and The Damaged Wheel)
- Setup and Arrangement of Measurements (section Test Setup)
- Execution of the Test Run (section Measurements and Run in Track)
- Evaluation of Results (section Results)
- Conclusion and Future work (section Conclusions)

1.1. The infrastructure

The infrastructure is managed by the Swedish transport administration. The maintenance status of this track is good in general, however some defects and degradations can always be found in some places; nevertheless these will not impact this investigation. The track is a single track with a gauge of 1435 mm with elastic fastenings that clamp the rail to the concrete sleeper. The rail is 60E1 with an inclination of 1:30 and a quality of R320Cr, and the rail was installed in 1994. The track carries axle loads of up to 31 tons, according to the maximum permitted axle load on iron ore trains. The tonnage on this track is about 18 MGT each year. The traffic on the current line is mixed between the iron ore trains (∼50 % of the traffic in terms of the number of wheels), other freight trains and passenger trains. The number of axles that pass this section is about 5000 each day, and the number of daily trains varies between thirty and sixty.

The wheel-defect detector is located in a section of straight track. The stiffness of the track was measured in 2022 with a track recording car equipped with a track stiffness measurement system [15]. The track recording car has a weight of 51 tons and an axle load of 12.75 tons. The track stiffness of this section where the detector is located is measured to about 40 kN/mm with a deflection of about 2 mm. This stiffness is what can be expected for this section after measurements totalling 16 km. The stiffness over the detector has no deviations from that of the track section in general. However, some minor deviation seems to be on the levelling of the track on and around the detector. Anyway, it can be assumed that this will not significantly impact the performance of the measurements for the detector. Nevertheless, the track, along with the detector, incorporates various types of fastenings, leading to potential variations in their dynamic behaviours. The track employs elastic fastenings featuring rail-pads, whereas the detector utilizes load cells. These differences may affect the dynamic force transmission between the track and the detector. However, these nuances are not demonstrated in the current quasi-static measurement of track stiffness. The track stiffness, the defection and the levelling are shown in Fig. 1, where the x-axis is the distance of 1 km. The position of the detector is defined as a dotted line in the figure about km 1163.5. The track stiffness measurements were done by a track recording car, which is in commercial use in Sweden.

1.2. Wheel defects in general

All infrastructure managers must deal with wheel defects that impact on the safety and the capacity of the track. There are two types of operational approaches for the railway. For those railways that have regulated traffic, only some operators are able to operate on the railway, while for those with unregulated traffic, all operators can apply to operate on the railway. In an unregulated market, more different operators and also types and statuses of wheels, are exposed on track. At the same time, the ambitions of companies differ in terms of asset management, and this can mirror the population of defective wheels on the track. Wheel tread damage for different forms has been described by Deuce [16], and out-of-round wheels have been comprehensively described by Nilsen [17]. The causes of locomotive wheel tread polygonization are elaborated by Fröhling et al. [8] and elaborate in the theory of self-excited vibration and mechanism of polygonal wear by Don and Cao [18].

This investigation will look in to a wheel with discrete wheel tread irregularity, this is a deviation from the normal wheel radius of the wheel, a local surface damage, for more information of the see the composite of wheel out-of-roundness. Useful definitions of wheel out-of-roundness and alarm limits from different countries can be found in the mentioned article [14].

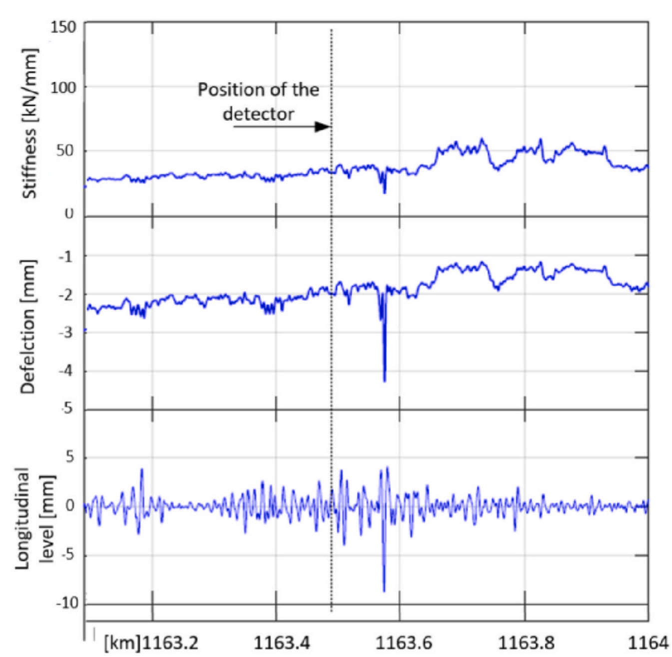

Fig. 1. Measurements of the track section with the detector. The track stiffness for the section is about 40 kN/mm, the deflection is around 2 mm and the longitudinal level is less than ± 5 mm.

The number of defective wheels reported by the WILD, and those that are reported to traffic control by other sources, at the public railway network in Sweden, is generally between 38 and 263 events each year. The absolute majority of these events come from the WILD. These impact the capacity on track via inspections of the track to ensure that no safety issues are found after an event. This is called delay time caused by defective wheels. The amount of delay time caused by defective wheels varies between 177 and 1925 h each year. Fig. 2 shows the number of defective wheels and the amount of delay time coming from defective wheels due to track inspections; the x-axis is the year and the y-axis is the number of events or the hours of delay. In 2018, defective wheels caused lots of delay time due to the extraordinarily harsh winters with many days of cold degrees across the entire country that caused lots of disturbance for the traffic in terms of train delay. However, with the exception of 2018, there is a trend of fewer defective wheels in each successive year.

A simple way too organise the wheel defects is to divide them into four different categories: surface defects, subsurface defects, profile defects, and polygonization; see Fig. 3. These can be further categorised into different subheadings, as shown below, see Fig. 3 [19]. The wheels in this investigation have surface defects, such as spalling and shelling. These defects are also referred to as rolling contact fatigue (RCF).

1. The Damaged Wheel

The damaged wheel investigated in this article is measured by laser; the defects can be seen in Fig. 4(a and b), with four different main damage areas: see arrows I, II, III, and IV. The largest damage found at the tread has a depth of 1.8 mm and has position III, as shown in Fig. 4 b). At the opposite side of the wheel are defects (Fig. 6 a) having a depth of 1.0 mm and represented at arrow I. In Fig. 4 b) is a line marked on the wheel that is 50 mm from the outside of the wheel (field side). Fig. 4 c) shows the inversed radii plot of the wheel at 50 mm from the field side of the wheel, where the four different defects are marked by I, II, III, and IV. The polygonalisation is measured for the wheel; this is presented in Table 1 for the four first orders: eccentricity, ovality, triangularity, and squarity. These can also be described as different orders of polygonalisation: first order of out-of-roundness, second order of out-of-roundness, third order of out-of-roundness, and fourth order of out-of-roundness; more on railway wheels and out-of-roundness is well described in Ref. [17].

The wagon was caught with force peak of 357 kN in a northerly direction at WILD in Norrmjöle, in the northern part of Sweden on March 17, 2018. When the force level exceeds 350 kN it is reported as a high-level alarm, and the vehicle needs to be immediately stopped, which was done with this wagon.

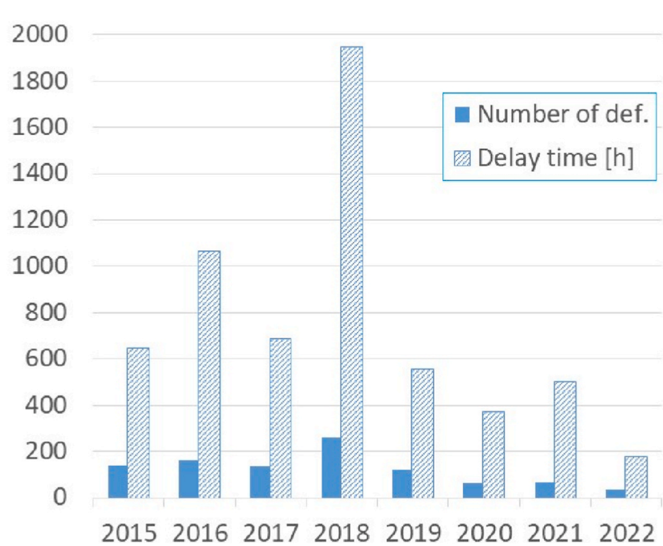

Fig. 2. Number of defective wheels from the Swedish railway network and its delay time for 2015 to 2022.

1.3. *wheel impact load detector*

The Wheel Impact Load Detector (WILD) is widely used as a checkpoint in railway; for instance, the Swedish railway network has about 30 of them spread over a railway network having a total length of 11 000 km. The WILD aims to identify wheels that are harmful to the track or that pose safety concerns. The wheel that triggers these alarms usually has some type of out-of-roundness, such as flats, spalling, or shelling, or some other type of defect [13]. The intention in having WILDs as part of the infrastructure is to protect the track from damage caused by wheels that have high vertical forces. Therefore, the systems are often placed in strategic sections of the infrastructure; for instance, where lots of cargo traffic goes or changes areas (as with borders), and at important connections (bridges), or, as in the current location, on a single track with no redundancy (important connections, e.g., between the mine and the harbour).

At least two types of wheel impact load defect detectors can be found on this track in Sweden: one with load cells, and the other based on fibre optic sensing. Strain gates technology can also be found, as in the case of a research station in Sävast [20]. The specific WILD that is examined in this investigation has eight sleepers equipped with load cells. The total length of this system is 4.8 m. This equipment measures the vertical load from the wheel.

For this infrastructure, the alarm limit for the peak forces is 350 kN. There are also other alarm limits, including the ratio and the warning limits (280 kN) that the rolling stock owner can use to indicate that the wheel needs to be maintained or changed. Fig. 5 shows a simplified principle of the wheel force response on a WILD. The y-axis is the force level, and the x-axis is the time. The wheel has the quasistatic load presented as a train load (Fl); the highest force response is identified as force peak (Fp), and the difference between these is the dynamic force (Fdyn). This work is only concerned with the force peak (Fp). The shape of this force response from a damaged wheel is shown in simulations [21].

1.4. *Test setup*

The field investigation was performed on April 26, 2018 in the railway network of the Swedish Transport Administration, Trafikverket, located on the southern loop of the Iron Ore Line, in northern Sweden.

The WILD that is the subject of this investigation is located at Sunderbyn. The detector is located in a straight section of the track and more than 3 km from the closest curve. This detector is built upon load cells and has a length of eight sleepers, with a total length of 4.8 m, as shown in Fig. 6. This WILD is a Wheelscan produced by Schenck Process GmbH.

The detector has been in operation since 2007. An estimated 25 million wheelsets have passed this detector since installation. This is the most common type of detector on the network.

The latest calibration was performed in April 2017. This detector was also inspected in May 2018 by measurements of the rail profile and the track gauge. The track gauge was on average 1440.5 mm over the eight sleepers, which compares with measurements taken before and after the detector with an average 2.3 mm wider track gauge. This measurement was taken with MiniProf rail measurement equipment. Regarding the rail profiles and track in general, everything was normal and unremarkable compared to the track outside the detector.

The train setup for the validation was two RC6E locomotives, one on each side, and the wagon with the damaged wheel was in the middle. The damaged wheel has the wheelset number 7 and is located on the left-hand side; see Fig. 7 for an illustration. The axle load for this axle is 14.4 metric tons. The time slot for this test is between 06:35 to 17:00, in between the regular traffic on this single-track section.

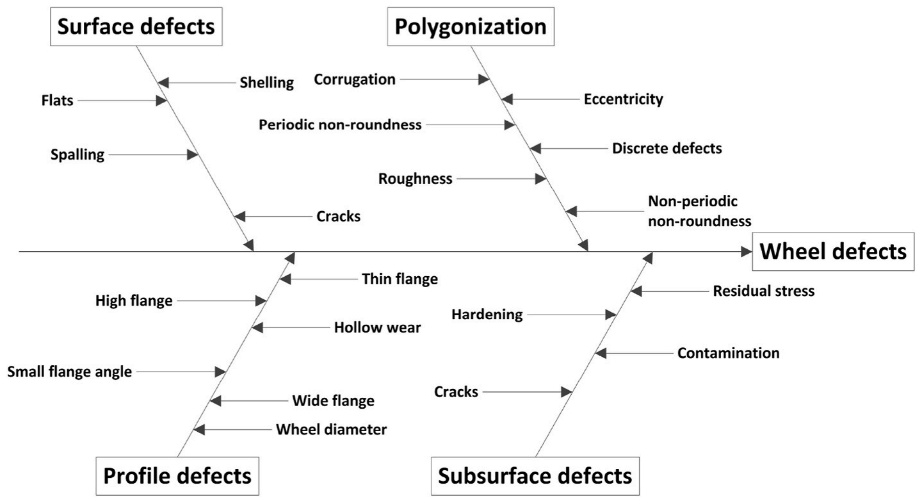

Fig. 3. Wheel defect divided into four different groups [19].

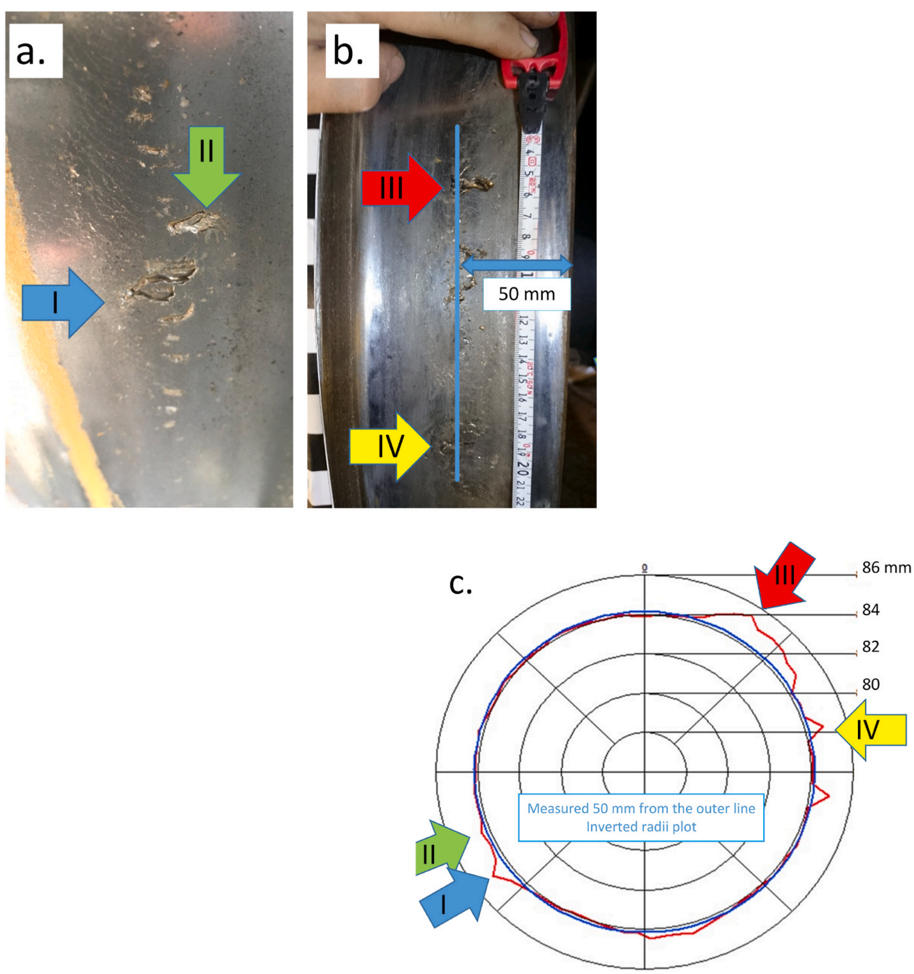

Fig. 4. Measurements of the damaged wheel, a) defect is at position I depth 1.0 mm, b) defect of position III with a depth of 1.8 mm, c) the inverted radii plot of the wheel at 50 mm from the outer side outer wheel.

1.5. Measurements and run in track

During the field investigation, the position of the wheel on the detector was documented lateral (by laser) and longitudinal (by photo). The lateral position is measured by laser to verify where the wheel is positioned during the passage over the detector: a bracket for the laser is mounted on one of the detector sleepers; see Fig. 8 for the measurement setup. The rail is the reference. The longitudinal position is monitored by marks on the wheel and rail.

The results from the lateral measurements are presented in Table 2. There are a total of 20 runs through the detector, ten in each direction, where two of the lateral measurements have no value for the lateral

Table 1
The measured polygonization of the wheel.

Polygonization	[mm]
Eccentricity	0.15
Ovality	0.2
Triangularity	0.17
Squarity	0.16

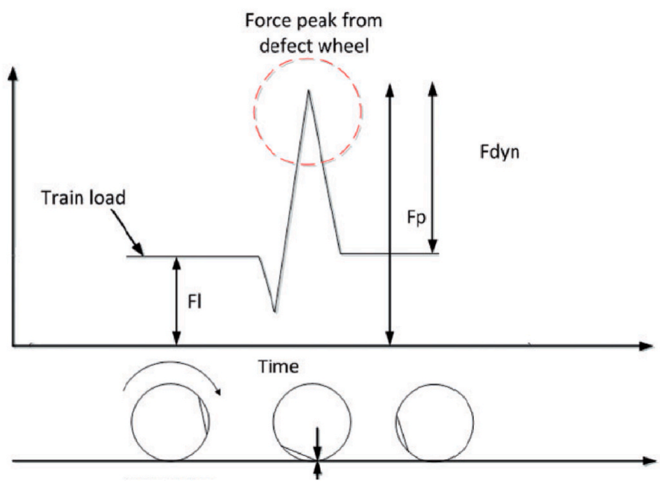

Fig. 5. The simplified principle of the WILD, y-axis force being response to the rail, x-axis being the time. Fl = the static train load, Fdyn = the dynamic response and Fp = total force response to the rail from a wheel.

Fig. 6. Wheel defect detector at Sunderbyn.

position (a). The running sequences were randomized to avoid systematic errors.

The longitudinal position for the wheel was also monitored. This was done by marking the wheel and the rail to observe if the wheel would hit at the same position or close to the same position every time.

The alignment between the wheel and rail was good during lower speeds, until a speed of 55 km/h. After that, the length that the train needs to travel before it is permitted to run at 100 km/h is about 40 km from the test place impact, so the alignment was not as good as before. Fig. 9 shows the pictures from six runs during the investigation. The marks of the wheel and rail can be seen in Fig. 9 a). These were taken during the 12th run and at speeds of 10 km/h, the speeds before this had been 6 runs with 10 km/h and 6 runs with 55 km/h; in other words, one can say that the alignment is good. The blue arrow in each of the pictures shows the direction of the moving train. For the 13th run with a speed of 55 km/h, the agreement is not as good as before. However, the deviation is not more than about 100 mm; see Fig. 9 b). Fig. 9 c) and d) show speeds of 100 km/h in which the deviation increased, while in the following run the deviation has decreased (Fig. 9 e). Furthermore, in Fig. 9 f), the position of the marks seems to indicate that the difference is about 600 mm (*a slipper space*). The likely reason for this variation in alignment between the wheel and rail has to do with the length of travel. The train needs to pass a certain position on the track to be able to reach

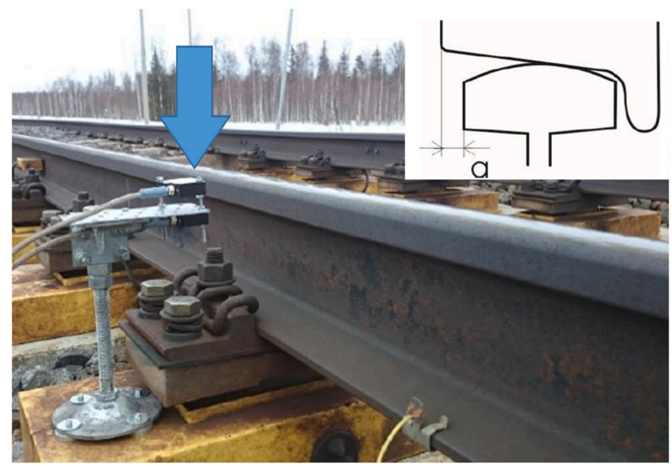

Fig. 8. Measurements of the lateral position of the wheel during the test of the response from defect wheel, photo by Dan Larsson DAMILL AB.

Table 2
The lateral measures during the test of the response from the defective wheel; the table include time, speed and the measure of the lateral position of the wheel according to Fig. 8.

Direction towards Boden (odd)			Direction towards Luleå (even)		
Time	**Speed (km/h)**	**a (mm)**	**Time**	**Speed (km/h)**	**a (mm)**
06:53	55	14.2	07:07	55	16.9
07:20	10	15.9	07:32	10	18.8
07:41	55	14.2	07:52	10	18.8
08:07	10	16.0	08:16	55	16.6
08:26	10	16.2	08:36	55	17.7
08:43	55	14.8	08:53	10	18.8
09:02	55	14.5	12:00	100	–
12:21	100	14.3	12:47	100	21.0
13:00	100	–	13:33	100	17.1
13:47	100	17.1	14:21	140	18.2

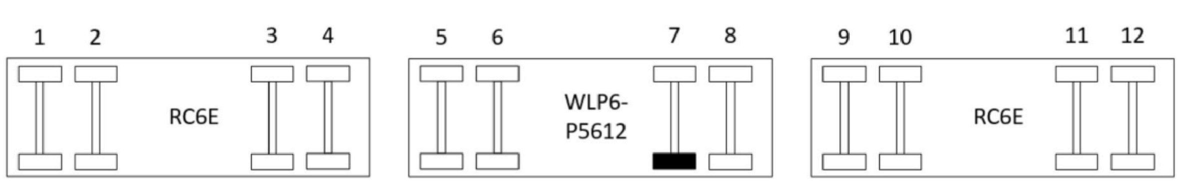

Fig. 7. The train configuration during the test in Sunderbyn, two locomotives (RC6E) at each side and in the middle the wagon with wheel damage at the left wheel in axle 7.

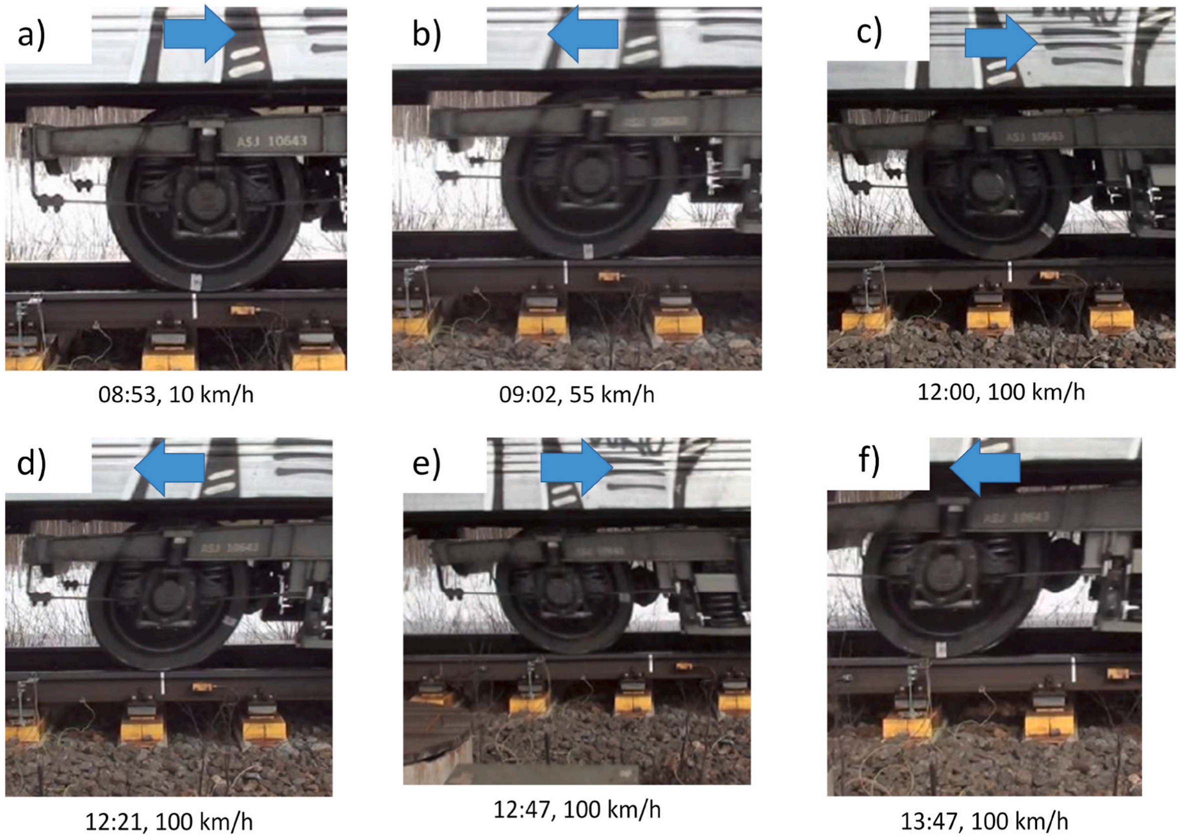

Fig. 9. The longitudinal positions of the wheel and rail for the different runs: a) the mark at the rail and wheel at the same position, b) all 13 runs with speeds up to 55 km/h the position are about 100 mm shifted from the start, c) the run 14th and the position between the rail has been moved with about 300 mm, d) the run 15th shows a larger difference between the marking, e) the 16th run aligns quite well with the marker at the rail and the wheel, f) the second last run and the position between the marker on the wheel and rail differs with about 600 mm. Photos by Dan Larsson DAMILL AB.

a speed of 100 km/h; this is due to the signaling system. The difference between the lateral positions over the detector differs between the traveling directions by an average of 3.0 mm.

2. Results

The number of approved runs is 16, 3 measurements for 10 km/h, 7 measurements for 55 km/h, and 6 measurements for 100 km/h. The exponential and the linear regression have the same value of the coefficient of determination, respectively $R^2_{exp} = 94.7$ and $R^2_{lin} = 94.3$. The simplest of these is the linear expression, which was selected in this work. The R^2 is the variation in percentage that explained the model. In this case, the R^2 is higher than 94 %, which can be interpreted as a good description of this model based on the measurements. Finally, the R^2 (adj) is adjusted to the number of measurements that, in this case, are 16 in the relation to the predicted response. However, the R^2 (adj) is close to the R^2, which means that the number of measurements is in a good range, and more of them should not change the result or the model so much. The investigation shows the force response was not the same in both directions connected to the speeds.

In other words, the most appropriate expression is the linear equation due to the good fit and simplicity. The formula for the force response expressed in Equation (1) was that each change in speed km/h changed the force response by about 0.9 kN. The constant in equation 74.98 is the quasi-static wheel load expressed in kN.

$$y = 74.98 + 0,9005v \tag{1}$$

Fig. 10 presents the result where the x-axis represents the speed of the train and the y-axis represents the response measured force. The Figure includes 16 measurement points at 10 km/h, 55 km/h, and 100 km/h, and the linear regression line includes the line for 95 % of the confidence interval and 95 % of the prediction interval.

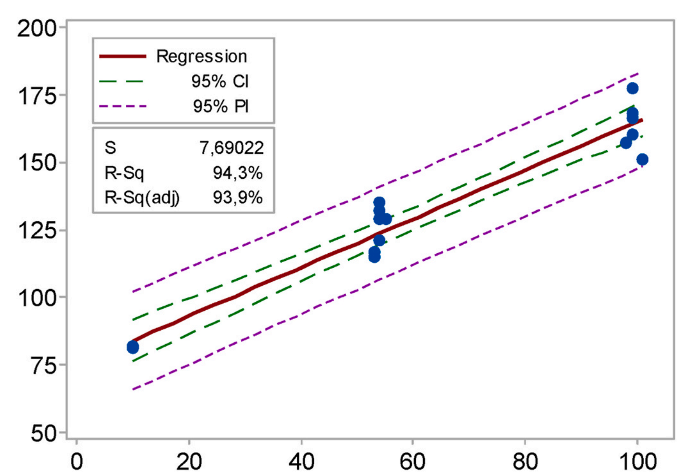

Fig. 10. The fitted line plot with the measurement results from the runs over the detector.

The prediction interval is the line that shows likely further responses of this specific wheel at certain speeds in the range of 10–100 km/h.

Roughly, this means that the further response of this wheel can give a force level between about 100 and 140 kN at a speed of 55 km/h and 140 kN–180 kN at a speed of 100 km/h. The variations are about 40 % at the speed of 55 km/h and 30 % at the speed of 100 km/h.

The *S*-value represents how the value differed from the fitted value and has a unit of kN in this case, indicating a lower value of S that better fit the model that describes the phenomenon.

At speeds of up to 55 km/h, the force response was larger in the direction south (Luleå) within about 14 kN and speed above 55 km/h, while the force response was larger in the direction north (Boden) with about 10 kN. Different traveling directions also had a slightly different lateral position of the wheelset on the track in this position.

By examining axle 8 and the right-hand side wheel according to Fig. 7, it is observed that the relationship between speed and force response is weaker, around 0.065 kN for each km/h. This value is less than 10 % of what a defective wheel generates. However, it's worth noting that the wheel on axle 8 comes from the same vehicle that has been in same operation and may have minor defects.

One must bear in mind that the WILD in this investigation is a type from an older generation. Nowadays, these types of WILD are intended to be replaced by new systems with more sophisticated setups for measurements.

3. Conclusion

The current investigation deals with the force response from a defective wheel on a wheel impact load detector in normal service, exposed to the defective wheel at different speeds and directions over the wayside detector station. The wheel defect detector is a typical model of detector of the kind used in the infrastructure for alarm abnormal wheels and was installed in 2007. The track stiffness over the detector is in the normal range of what can be expected, and no too large deviations with the leveling of the track due to this area.

The goal is to verify the impact of the speed in terms of the force response of the defective wheel. The wheel was described before the runs and the defects of the wheel resulted from normal service. This wheel has typical defects that occur in service during the winter season in Sweden. The wheel had local damage at a depth up to 1.8 mm and also un-roundness up to 0.2 mm, as well as other smaller defects.

The main contributions, and within the speed limit of 10–100 km/h, of the current work are.

1. the relation between speed and force response are linear.
2. the force response is 0.9 kN for each km/h.
3. the force response differs depending on the running direction by about 10–14 kN, depending on the speed.

Future work should repeat this type of test with other defective wheels to get more data on the force response, and with wheels with regular flatness. The response of wheel defects at speeds above 100 km/h are also of interest, to fill the knowledge gap regarding the force response of defective wheels. This would increase the confidence of force response on track from wheel defects and be able to predict the force for a certain defect and speed. Also, the track stiffness could have an impact on the force response from a wheel defect detector; this could be investigated in the future.

CRediT authorship contribution statement

Matthias Asplund: Investigation, Methodology, Project administration, Writing – original draft. **Pär Söderström:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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