



Research report 2025:02

Use of wheel load detector data to predict risk of track damage

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Reducing traffic disruptions and damage to track and vehicles through improved regulations and procedures

Use of wheel load detector data to predict risk of track damage

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18th May 2026

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The current report investigates how wheel load detectors can be used to identify damaged wheels that may cause excessive track damage. In this context, relevant forms of wheel and track damage are presented. Current detector use including limitations and potential enhancements are discussed. Procedures to detect and classify damaged wheels using a stepwise enhancement of the current detector network are outlined, and an example of using detector data to predict rail crack growth and fracture is presented. Possibilities and challenges for operational implementation are outlined.

Denna rapport behandlar hur hjulskadedetektorer kan användas för att identifiera skadade hjul som riskerar att orsaka omfattande spårskador. I detta sammanhang presenteras relevanta typer av hjul- och spårskador. Vidare diskuteras nuvarande användning av detektorer, inklusive deras begränsningar och möjliga förbättringar. Rapporten beskriver även procedurer för att detektera och klassificera skadade hjul genom en stegvis utveckling av det befintliga detektornätverket. Dessutom ges ett exempel på hur detektordata kan utnyttjas för att prediktera spricktillväxt i räler samt risken för rälsbrott. Slutligen diskuteras möjligheter och utmaningar kopplade till en operativ implementering.

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1 Introduction

Within the context of reducing traffic disruptions and damage to track and vehicles through improved regulations and procedures, the focus of the current report is on employing wheel load detectors to avoid damaged wheels causing excessive damage to the track. To this end, the report sets out with an overview of relevant forms of track damage with a discussion on how high wheel loads are related to different forms of track damage. This is followed in chapter 3 by a discussion on uncertainties in detector measurements and how this relates to the establishment of limit loads.

Chapter 4 provides an overview of relevant forms of wheel damage. It is discussed if and how these forms of damage can be detected and classified by wheel load detector data. Based on this, chapter 5 outlines how improved detection and classification of damaged wheels could be achieved using a stepwise enhancement of the current detector network.

Finally, chapter 6 presents an example of how detector data can be employed to predict rail crack growth. Possibilities and challenges for operational implementation are indicated.

2 Assessment of track damage and derailment risks

2.1 Rail crack growth and risk of rail breaks

2.1.1 Influence of wheel load on rail break and crack growth

The loading of a (larger) crack¹ in the rail can be quantified by the stress intensity factor

$$K_I = f\sigma\sqrt{\pi a} \quad (1)$$

here f is a geometry factor that depends on the position, shape and size (a) of the crack, the geometry of the rail, and the type of loading, see figure 1. Further, σ is the applied nominal stress. If we exclude residual stresses² the stress contains a quasi-static contribution due to restricted thermal contraction of the (continuously welded) rail

$$\sigma_t = E\alpha\Delta T \quad (2)$$

where $\Delta T = T_0 - T$, with T being the current rail temperature and T_0 the stress-free temperature.

¹Large enough that the propagation is driven by tension (mode I) and can be analysed within the framework of linear elastic fracture mechanics. This corresponds to some millimetre long foot cracks and some 4–5 mm deep railhead cracks.

²Reasonable since the magnitude of the residual stress is often compressive but of unknown magnitude. Ignoring the residual stress is then on the safe side.

Further, there is a transient component related to rail bending

$$\sigma_b = \frac{M}{I}h \quad (3)$$

where M is the bending moment, I the moment of inertia and h the distance from the neutral axis of the rail to the bottom of the rail foot (for rail foot cracks) or top of the rail head (for rail head cracks), see figure 1.

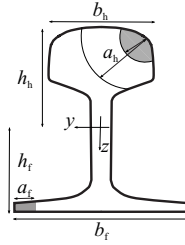


Figure 1: Geometry of a rail section with headcheck and foot crack. Index ‘h’ indicates head, and index ‘f’ foot.
From [5].

Here M will depend on the wheel load, the vehicle type and speed, and track conditions, see [5]. The maximum bending moment due to passing wheel can generally be expressed as

$$\max\{M\} = C_0 + C_1 \left(\frac{F_{\max}}{F_{\text{ref}}} - 1 \right) \quad (4)$$

Where $F_{\max}$ is the maximum impact force, F_{ref} is a reference value, and C_0 and C_1 are coefficients. Values of the coefficients F_{ref} , C_0 and C_1 can be found in [11] for different combinations of vehicle types and track stiffness, including hanging sleepers.

Rail break occurs when

$$K_I = K_{Ib} + K_{It} \geq K_{Ic} \quad (5)$$

where K_{Ib} is the stress intensity due to bending, K_{It} due to restricted thermal contraction, and K_{Ic} is the fracture toughness. This can be reformulated as

$$K_I = K_{Ib} \geq K_{Ic} - K_{It} \quad (6)$$

Magnitudes of K_I for different combinations of vehicle type and track stiffness are compared to values of $K_{Ic} - K_{It}$ for different temperatures in figure 2.

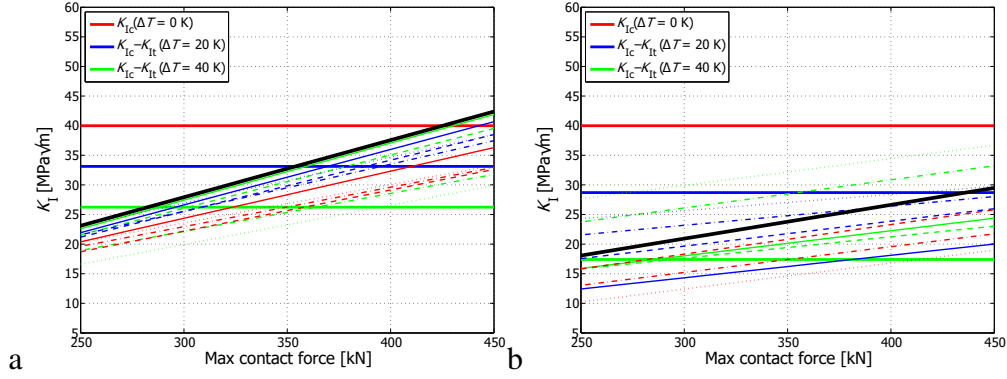


Figure 2: Stress intensities, K_{Ib} , due to bending in a 60E1 rail with a
a) 5 mm foot crack, b) 25 mm head crack

Influence of hanging sleepers is accounted for. Vehicle type indicated by colour, and ballast stiffness by line type. Fracture toughness reduced by thermal stress intensity is indicated by solid horizontal lines as ΔT : 0°C: red, 20°C: blue and 40°C: green. The thick black lines indicate “bad case” scenarios.

From [5].

As seen from figure 2, the magnitude of K_{Ib} is only moderately affected by the maximum impact force for the case of a rail head crack, which is often the most dangerous case. In the case of a rail foot crack, the impact force has a somewhat higher influence, but it is still fairly limited. The temperature will have a significant effect in both cases.

2.1.2 Procedure to predict rail crack growth

To estimate the growth rate, an unmodified Paris law can be used. This involves some simplifications, but a more complex model would increase the uncertainty due to the lack of reliable input data.

$$\frac{da}{dN} = C(\Delta K_I)^m \quad (7)$$

Here da is crack growth per cycle dN , C and m are material parameters. Further

$$\Delta K_I = K_{I, \max} - \max \{K_{I, \min}, 0\} \quad (8)$$

where

$$K_{I,\max} = \max_t (\sigma_b(t) + \sigma_t(t)) f \sqrt{\pi a} \quad (9)$$

$$K_{I,\min} = \min_t (\sigma_b(t) + \sigma_t(t)) f \sqrt{\pi a} \quad (10)$$

where t indicates time.

Note that $\sigma_t(t)$ is constant during a load cycle (i.e., a wheel passage). Consequently, it will only influence predicted crack growth rates when $K_{\min} < 0$. This may be on the unsafe side.

The effect of a load increase on crack growth is rather larger since the growth rate will essentially include the bending stress cubed since $m \approx 3$. However, a single overload will have an insignificant effect on the overall growth of a rail crack³. Here it is more the increased scatter in the load spectrum due to for example wheel polygonisation on multiple wheels that is important.

To employ Paris law for crack growth predictions, the following steps are required.

1. Decide which vehicle type(s) to consider.
2. Decide which local track geometry fault(s) influencing the vertical load that should be included. Decide if they should be positioned along the track, or considered as statistical scatter (or bad case scenarios) in amplifying wheel loads.
3. Collect track stiffness data and decide which track stiffness magnitudes (including hanging sleepers) to consider. Decide if they should be positioned along the track, or considered as statistical scatter (or bad case scenarios) in evaluating bending moments from wheel loads.
4. Collect the time history of the load.
5. Translate the (amplified) load spectrum to equivalent rail bending moments using related track stiffness magnitudes, see equation 4
6. Evaluate load cycles and min and max forces for those cycles. Here a rain-flow count algorithm may need to be employed to identify load cycles.
7. Collect crack size distributions, and select initial crack sizes to consider.
8. Decide which rail temperature spectrum to employ and how it should be correlated to pertinent wheel passages. A consideration is required on how fine-grained this correlation should be, i.e., seasonal variations or daily variations.
9. Perform a crack growth analysis (e.g., cycle-by-cycle integration) to derive crack size evolution to fracture. For each cycle:
 - a) evaluate bending (equation 3) and thermal (equation 2) stresses,

³It may however have a significant effect on deterioration of the running gear, cf. [8]

- b) for the current crack type and size, evaluate the geometry factor f , see e.g., [12],
- c) evaluate $K_{Ib,max}$, $K_{Ib,min}$ and K_{It} , and derive ΔK_I ,
- d) derive crack growth increment, da/dN (material parameters commonly used are $C = 2.47 \cdot 10^{-9}$ and $m = 3.3$ which apply to da/dN in mm/cycle and ΔK_I in $MPa\sqrt{m}$),
- e) check rail fracture (i.e., $K_{Ib,max} \geq K_{Ic} - K_{It}$).

A detailed analysis will be extremely complex and require huge amounts of data that are commonly not available. A recommended strategy is therefore to initially consider simplified load scenarios where many parameters are kept constant. This will provide an idea of the operational life, and also the influence of different parameters. The concept will be further discussed in chapter 6.

2.2 Sleeper cracking

Quantifying the risk of sleeper cracking due to overloading is very complex since it will be highly influenced by the stiffness distribution below the sleeper, see [1]. Regardless, both sleeper bending moment and the stress range of the reinforcement are essentially linear functions of the wheel impact load, as seen in figure 3. Note that the increase in reinforcement stress range increases faster with wheel impact load magnitude than the rail bending stress, cf. figure 2. This would need to be accounted for if the allowable wheel impact load magnitude would be based on the risk of sleeper cracking. However, sleeper cracking is not a direct safety issue of the same magnitude as a rail break, although it can be costly and require corrective maintenance.

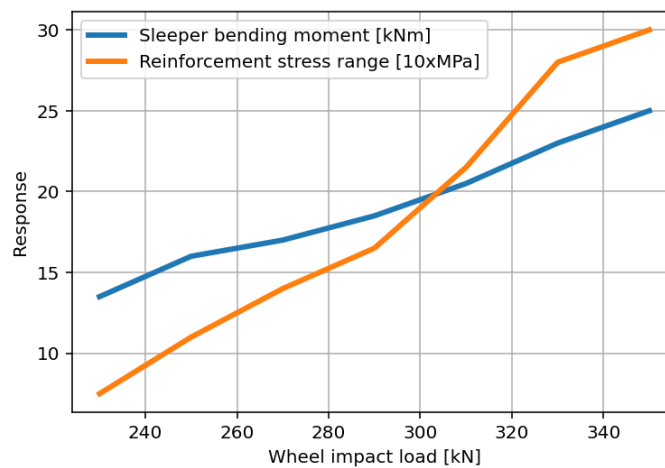


Figure 3: Sleeper bending moment and stress range in the reinforcement as function of wheel impact load magnitude.

Derived from data in [1].

2.3 Ballast settlement

Wheel impact loads should in general not have a major effect on ballast settlement. The reason is that impact loads are fairly rare from the perspective of a point along the track. The impact loads also occur as local forces on the rail, but will be spread out over some sleepers before being distributed to the ballast. Thus the effect on the ballast will not be as severe as for the rail. If there is a weak point in the track structure the overload could of course still cause issues. But overall the influence of overloads related to wheel damage should be small.

Another phenomenon that will affect settlements is general overloading of wagons. This will also affect the deterioration of bridges and other support structures. Typically, the safety factors are high for these structures, so there is normally no immediate risk of failure. However, if the overloading occurs frequently, fatigue cracking etc. can be accelerated and require premature repairs or replacements. General overloading will also increase loading in curves, which will accelerate e.g., surface initiated RCF in the rail, see e.g., [4]. General overloading is however considered to be outside the scope of the current study since settlements relate strongly to local track conditions, and current wheel load detectors have relatively accurate measurements of average (quasi-static) loads (however, see the reservation in chapter 3).

2.4 Flange climbing

A more detrimental issue related to loading is skewed or generally unbalanced loading. This may in combination with track geometry faults, such as skewing, cause flange climbing that may lead to derailment, see figure 4. Naturally, one challenge here is to decide how severe track faults that should be considered.

As current detectors have (as mentioned) a fairly accurate measurement of average (quasi-static) loads, the situation can from that perspective be handled fairly well by current equipment. What complicates the analysis is the identification of individual wagons. This is further complicated by the existence of single axle bogies, and Jacob bogies.

As flange climbing is more of an ‘equipment identification issue’ and strongly related to local track faults, it is considered outside the scope of the current study.

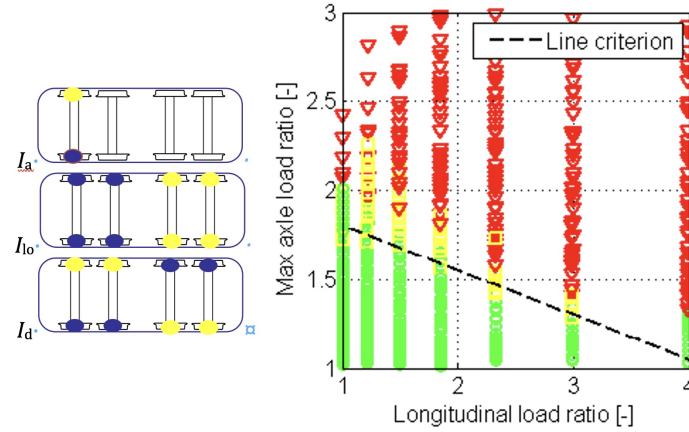


Figure 4: Risk of flange climbing (yellow) and derailment (red) for wagons with combined axially (I_a) and longitudinally (I_{lo}) unbalanced loading. From [6].

3 Uncertainties in detector measurements

Scatter in measured wheel loads has been thoroughly investigated in [10]. In short, the scatter can be related to (more or less) stochastic measurement uncertainties, systematic measurement deviations, and/or deviations related to impact load characteristics.

- Stochastic measurement uncertainties provide a limit on how exact the measurements can be. In practice they are however very difficult to distinguish from e.g., deviations related to impact load characteristics.
- Systematic measurement deviations can for example be related to the placement of a detector in a curve or on a softer trackbed. In theory systematic measurement deviations can be compensated for by calibration. In practice, this should be feasible for (quasi-static) average load, but difficult for dynamic impact loads. The case is complicated by the fact that some causes of systematic measurement deviations may evolve over time. Examples are track geometry faults, and track stiffness at the detector site.
- Deviations related to impact load characteristics are perhaps the most difficult to handle. In addition they do not really relate to measurement uncertainties. Instead they relate to issues in relating a certain wheel damage to a specific wheel impact load magnitude. This is not feasible in general since the impact load magnitude will depend on axle load and speed of the vehicle, and also the impact position along the detector. These factors can, at least in theory, be compensated for through the support of numerical simulations. More challenging are deviations due to differences in lateral positions of wheel defects on the wheel tread. If this position is not (or only partly) located in the running band during the passage of a wheel detector the damage will not induce any (large) impact load, cf. [10].

As a result of all these phenomena, there will be significant deviations in measured load magnitudes for the same wheel flat also at operations featuring the same speed and axle load. In [10] measured impact load magnitudes from the same wheel flat on an empty train passing several detectors at similar speeds are compared. The measured peak loads were found to vary up to a factor of around two. In addition, comparisons of measured average (quasi-static) loads and impact loads for studied wheel flats on wheels passing several detectors indicated systematic deviations between the detectors.

3.1 Relation to impact load requirements

The intention with wheel load detectors is to stop trains that may cause severe damage to the track and/or to the vehicle. Given the massive scatter in measured impact load magnitudes, it can be discussed whether it's suitable to base this decision on the impact load. An alternative would be to base it on the wheel damage length in the circumferential direction. Some major complications with such an approach are that

- The wheel damage length is not a well-defined measure.
- Wheel damage with long circumferential extension, or in the form of polygonisation may generate very high loads but be very hard to detect visually, cf. [9, 7].
- There is no clear correlation between damage length and impact load magnitude. Here damage depth is better, but complex to measure in field.
- Wheel damage measurements in operation are not beneficial from a workers' safety perspective.

These issues make such an approach less appropriate. Current regulations at Trafikverket [14] employ measured loads or wheel damage length to classify the severity. The load magnitude combined with the measured wheel damage length (and current temperature) are employed to decide if there is a need to inspect the track that the damaged wheel has passed.

A pragmatic approach to enhance current procedures would be to eliminate – as far as possible – all systematic and stochastic deviations in the measurements. This leaves deviations caused by the impact load characteristics. Those deviations can be decreased by analysing wheel load histories (over subsequent detector passages, and during a passage), and/or gathering of data from additional wheel load detectors in curves, and/or employing profile measurements, see section 5.

4 Framework for categorising wheel tread damage

4.1 Use of detector data to manage wheel tread damage

The type of wheel load detectors considered here measure vertical loads. Thus, they can only detect tread damage that influences the vertical load. For such defects, the detector data can (ideally) be used to

- Categorise the type of damage to guide the identification of suitable maintenance actions.
- Estimate the extent of damage to guide maintenance scheduling
- Ensure whether the load magnitudes are below alarm (and alert) limits to protect the track and preferably mitigate wheels before they cause traffic disruptions through catastrophic failure or by being slowed down or halted on the line.

In the following some common types of wheel tread damage are presented in section 4.2. This is followed in section 4.3 by an overview of if and how these types of damage can be detected and analysed using wheel load detector data.

4.2 Types of wheel tread damage

A brief summary of some relevant types of wheel tread damage is presented. More in-depth descriptions can be found in [2, 13].

4.2.1 Indentations

Indentations caused by gravel as in figure 5 are normally benign and prone to wear off especially if they are smaller than the size of the wheel–rail contact area. Deeper ‘cut-like’ indentations can be caused by poorly maintained joints, switches & crossing details etc. These are likely to remain, but to the authors’ knowledge there exists no studies on whether they are prone to cause progressing damage.



Figure 5: Indentations caused by gravel

4.2.2 Wear

Flange (figure 6a) and tread (figure 6b) wear will have a substantial influence on vehicle steering, wheel–rail contact conditions etc. The influence on vertical force magnitudes is however minor. As a consequence, these types of damage are not likely to be detected in a wheel load detector.

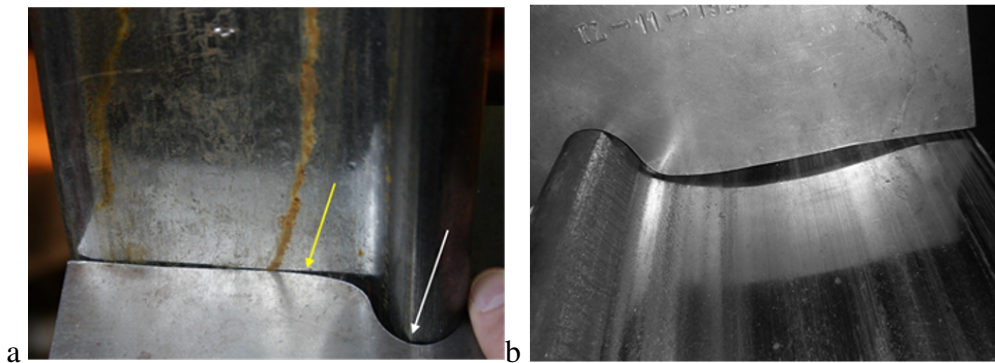


Figure 6: a) Flange wear, b) Hollow wear

Wheel polygonisation caused by periodic wear is a phenomenon similar to rail corrugation. It will cause a rather high frequency, often narrow band, load that can reach high magnitudes if the polygonisation is allowed to proceed.

4.2.3 Rolling contact fatigue (RCF)

Regular surface initiated RCF, as seen in figure 7a should trigger fairly urgent re-profiling of the wheel. The influence of vertical forces is initially minor but will increase somewhat with progressive material fallout, see figure 7b. If the material fall-out continues it may result in an RCF cluster as seen in figure 8a. Such a cluster constitutes large-scale fall-out that may extend several decimetres along the wheel tread. This will cause very high impact loads that may exceed alarm limits.

Note that surface initiated RCF commonly occur on the field side of the wheel tread as caused by contact with the inner rail during curving. Such cracks will not give any indication when passing a detector on tangent track unless they grow into the nominal running band.

Rolling contact fatigue can also initiate below the surface, see figure 8b. Such a crack will not cause any major increase in vertical loading of the wheel until wheel tread fracture occurs. After fracture vertical forces are very high and likely to exceed alarm limits.

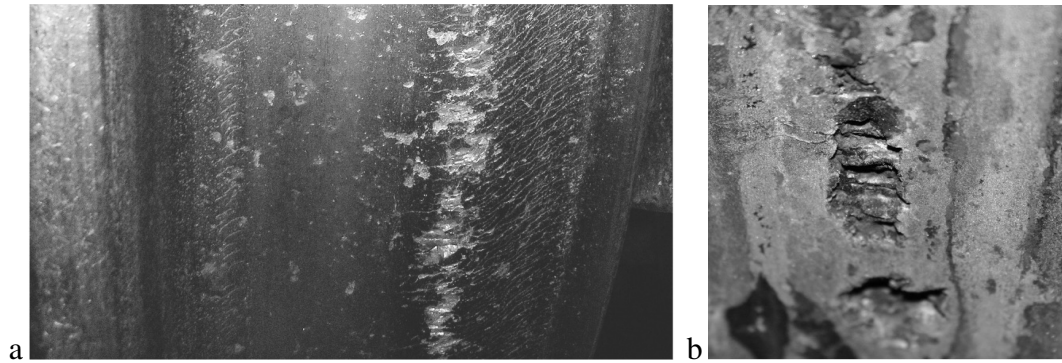


Figure 7: a) Severe surface initiated RCF, b) RCF material fall-out



Figure 8: a) RCF cluster with material fall-out in a long segment, b) Subsurface initiated rolling contact fatigue fracture.

4.2.4 Thermal damage

Short-distance (decimetres) sliding of the wheel on the rail may cause thermal facets as seen in figure 9a. These will not cause any major increase in vertical loads. Small facets may wear off. However facets may act as initiation sites for surface initiated RCF due to the induced tensile residual stresses and small-scale thermal cracking. The induced RCF may then evolve to RCF clusters. This motivates why also fairly small thermal facets may require wheel reprofiling.

Wheel–rail sliding over a longer distance (metres) will result in a wheel flat (see figure 9b) that will induce rather high impact loads. The wheel flat may be surrounded by brittle martensite. If the martensite falls off, impact load magnitudes may slightly increase. However, after that short-term increase impact load magnitudes tend to decrease due to rounding off of wheel flat edges.

Wheel flats may be very long (on the order of decimetres). Such long wheel flats may induce very high impact loads that may exceed alarm limits and thus require the train to reduce speed or stop. They may however be very hard to detect in visual inspections, see [9].

Note that wheel flats (and thermal facets) are local phenomena. If formed during curving (i.e., inside or outside the nominal running circle) they may not cause high impact load magnitudes when passing a wheel load detector on tangent track, and thus remain undetected.

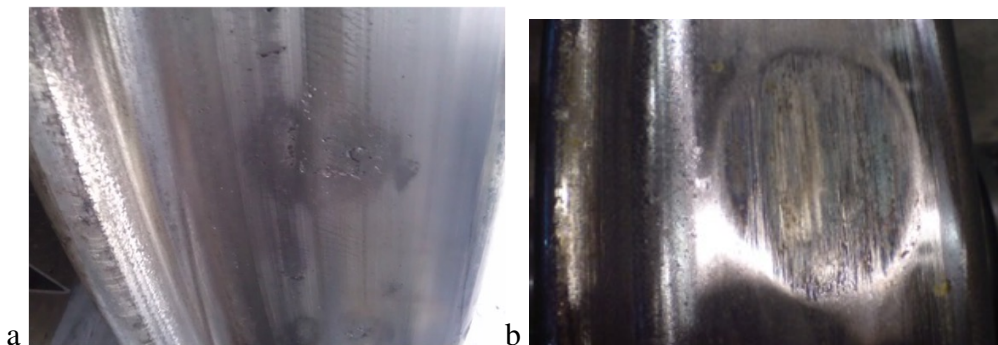


Figure 9: a) Thermal facets, b) Wheel flat

Overheating of a wheel induces tensile residual stresses that can result in thermal cracking. A minor overheating typically results in a ‘brick’ or ‘crocodile skin’ pattern of shallow radial cracks, as also often seen in thermal facets, see figure 9a. More aggressive heating results in radial cracks, see figure 10a. Excessive overheating will drive the radial cracking deeper into the rim and potentially into the disc, see figure 10b. In extreme cases the crack may propagate into the hub.

Since there is only a minor effect on the wheel tread of thermal cracks, smaller cracks will not give any indications in wheel load detectors. However, if the wheel flexibility is severely altered by large scale cracking, there may be larger impact

loads. This is especially the case when parts of the wheel tread detaches. Such wheels also pose significant derailment risks.

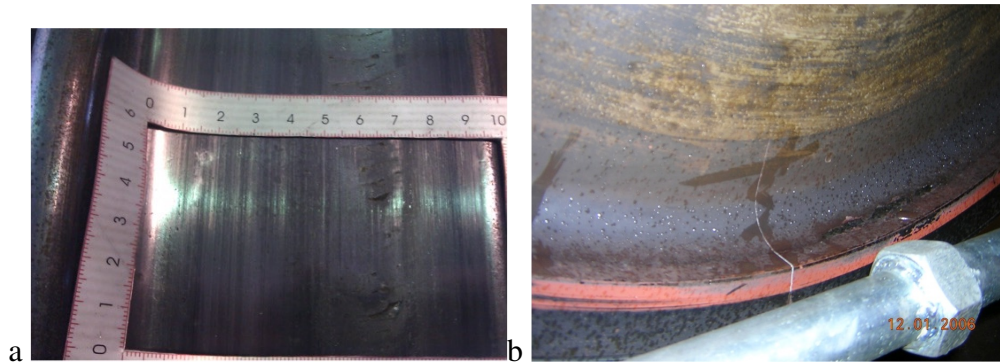


Figure 10: a) Small radial thermal cracks, b) Progressive radial wheel cracking

4.3 Wheel damage classification

An overview of common types of wheel tread damage is presented in table 1. The table indicates

- Whether the damage type is detectable in a wheel load detector.
- How the damage type can be classified using the wheel load detector data.
- If the wheel damage type is likely to cause damage to the track.
- If the damage type is likely to generate load levels that exceed alarm limits (reduced speed or stop) or alert limits (information sent to operator for maintenance planning).
- If wheel load detector data can be used to assess current status (i.e., level of damage) of the wheel.

Damage type	Detectable	Classification	Risk of track damage	Risks exceeding limits	Status evaluation
Indentations	Only very large (in circumferential direction)	High frequency, low magnitude load pulse with wheel circumference periodicities. Magnitude normally decreasing over time.	Minor	Minor risk	Potentially for large indentations
Tread wear	No	–	Can damage crossings	–	–
Flange wear	No	–	Moderate	–	–
Polygonisation	Yes	Moderate magnitude, narrow frequency load	Moderate	If extensive	Possibly with time history
Surface RCF	Large scale regular RCF could be detectable	Large scale regular RCF could be manifested as high frequency low magnitude load. Depending on RCF extension the load can be periodic or continuous.	Minor, but may cause RCF cluster with major risks	Minor risk	Potentially possible to evaluate level and extension from time history.
Subsurface RCF	Not until propagated to failure	Very high magnitude load pulse with periodicity corresponding to wheel circumference. Instantaneous magnitude build-up that (initially) may decrease over time.	Major	Major risk	Load magnitude and time history give idea of depth and extent.
RCF cluster	Yes	Load pulse with periodicity corresponding to wheel circumference. Magnitude increases over time.	Major for large (i.e., long) RCF clusters	Major	Load magnitude and evolution inform of depth and extent.
Thermal facets	Larger facets could be detected	Low magnitude load pulse with periodicity corresponding to wheel circumference. If sufficiently large not to be worn off, magnitude builds up gradually over time.	Minor	Minor, but may cause RCF cluster	Should be possible from time history.
Wheel flats	Yes	Load pulse with periodicity corresponding to wheel circumference. Magnitude builds up instantaneously and then (initially) decreases over time.	Major for large (i.e., long) wheel flats	Major	Load magnitude and evolution during a roll-over gives idea of depth and extent, respectively.
Thermal cracks	No, unless very large	–	No, unless fractured wheel	Minor risk unless very large	No

Table 1: Wheel damage classification. Time history and frequency analyses require access to load history for passing wheels.

5 Recommended procedures

Currently, wheel load detectors are mainly used to detect wheel flats and RCF clusters. Only the load magnitude (average and maximum) is used. This detector strategy captures the most detrimental types of wheel damage. It however provides little support for maintenance planning. To improve this it would be beneficial to also collect and analyse wheel load histories from existing detectors. As seen from table 1, this would allow for much broader assessment. To obtain the load histories would likely require limited modifications of the detectors. It would however require a more detailed and complex data analysis and the need to store larger amounts of data. To some extent, methods for such analyses exist and can be further developed. However, before operational load history data are collected, there is no possibility to calibrate and validate models.

As discussed above, some types of damage, mainly wheel flats and local RCF, can be initiated during curve negotiations on a lateral position of the wheel which is not (or only partially) in contact with the rail when passing a load detector on tangent track. Such types of damage are in risk of going undetected until they reach a size that extends into the running band. On the other hand, they are usually not inducing a major risk for causing severe track damage until they have grown to that extent.

One possibility to capture also such defects would be to introduce load detectors also in curved track. Such detectors could be dedicated for maintenance purposes since defects entirely outside the tangent track running band should be fairly small. The detectors would thus not need to be very precise. They should however preferably collect the load history during wheel passage since it is mainly the extent and development of the defects (and not their impact load magnitude) that is important to follow. Note that this would require identification that allows to follow individual wheels between measurements, and also if they are running on the inner or outer rail in the curve. This, and the need for additional wheel load detectors, may make such an extension too complex and expensive in relation to its benefits.

Alternatively, wheel profile detectors may provide information on wheel damage outside of the running band. Current wheel profile detectors typically measure one or a few profiles of each wheel, which provides a sample that may, or may not, capture the wheel damage. If they were to measure the profiles along the entire circumference, they would provide full information on extension and position of tread damage. In addition, they would provide information on tread and flange wear. Wheel profile detectors would however not provide any information on load magnitudes. This is not altogether bad since the load magnitude depends on several factors (e.g., speed) in addition to the damage characteristics. Given the damage geometry, numerical simulations (possibly including a trained AI model) could be employed to evaluate impact load magnitude at different operational scenarios. This would allow for much more precise handling of individual cases of wheel damage than what is possible today. It would however require sophisticated simulation models and large-scale data handling and simulation capacities.

A summary of what could potentially be achieved with access to load history, wheel load detectors in curves, and wheel profile detectors is provided in table 2. Here, knowing the load spectrum implies that you can obtain an idea of magnitude and circumferential distribution of the wheel tread damage. For polygonisation you can for example derive the wavelength(s) of the irregularity from the frequency content (and operational speed). In addition, the load magnitudes would provide an idea of the depth/extension of troughs. In table 2 ‘thermal cracks’ implies small cracks. For larger cracks, see the discussion in section 4.2.4.

Damage type	Currently	Load history	Detectors in curves	Wheel profiles
Indentations	Max load magnitude from indentations in running band	Load spectrum from indentations in nominal running band	Load spectrum from indentations on the tread	Shape of irregularities
Tread wear	–	–	–	Tread wear shape
Flange wear	–	–	–	Flange wear shape
Polygonisation	Max load magnitude from irregularities in running band	Load spectrum from irregularities in nominal running band	Load spectrum from irregularities on the tread	Shape and localisation of polygonisation irregularities
Surface RCF	Max load triggered by RCF in nominal running band	Load spectrum from RCF in the nominal running band	Load spectrum from RCF on the tread	Shape and localisation of RCF induced surface defects
Subsurface RCF	No significant effect until propagated to (close to) fracture	–	–	–
RCF cluster	Max load triggered in nominal running band	Cluster length(s) in nominal running band	Indication of extension outside nominal running band	RCF cluster shape
Thermal facets	Max load triggered by facet in nominal running band	Facet length(s) in nominal running band	Indication of facets outside nominal running band	Facet shape(s) and position(s)
Wheel flats	Max load triggered by wheel flat in nominal running band	Wheel flat length(s) in nominal running band (although complicated by the transient load not being damped-out until a while after flat passage)	Indication of wheel flats outside nominal running band	Wheel flat shape(s) and position(s)
Thermal cracks	–	–	–	Not likely to be found unless large

Table 2: Possibilities for wheel damage detection with current detectors, with access to wheel load histories, with wheel load detectors in curves, and with additional scans of wheel profiles along the circumference.

Before any extensions from current practices are carried out, it is recommended that the analysis procedures should be developed and tested in simulations. This allows procurement of new installations etc to be based on actual data needs.

6 Assessment of operational scenarios

In this section we focus on employing wheel load detector data for an assessment of the influence of the load spectrum on rail crack growth. With current detector data essentially average and maximum load magnitudes are available. A decision must then be made on how these quantities should be translated to a load spectrum: An extremely conservative estimation is to use the maximum load for all load cycles caused by that wheel. An estimation on the unsafe side is to only use the average load. More reasonable estimation is to use the maximum load for $X\%$ of the load cycles caused by the wheel. However, current detector data does not permit us to estimate what X should be since the load history during a detector passage is not collected.

As discussed in section 2.1.2, a full analysis of crack growth considering all different vehicle types, the entire load spectrum, the entire range of initial crack sizes, all temperature variations, and variations in track stiffness would be unmanageable. Here, a simplified analysis is demonstrated where the influences of various operational and maintenance practices are shown. To that end, all but one parameter are kept constant. Figure 11a shows example output in terms of crack size evolution of a rail foot crack. In particular, the influence of temperature and load is shown.

It can here be noted that Paris law is history independent. The influence of initial crack length a_{ini} can thus be obtained by entering the curve at a suitable initial crack length. For example, at $\Delta T = 0$ °C and $M_{max} = 30$ kNm, it is seen from figure 11a that approximately 75% (2 of 2.6 million cycles) of the service life is spent propagating the crack from 1 mm to 5 mm. For a foot crack this implies that larger cracks must be urgently removed. For rail head cracks there is a similar trend which could imply that early grinding would be beneficial since it keeps crack small and growing at a slow rate. Caution is however needed since small railhead cracks are mainly driven by the contact stress field and not bending, thus violating restrictions for the analysis stated in section 2.1.1.

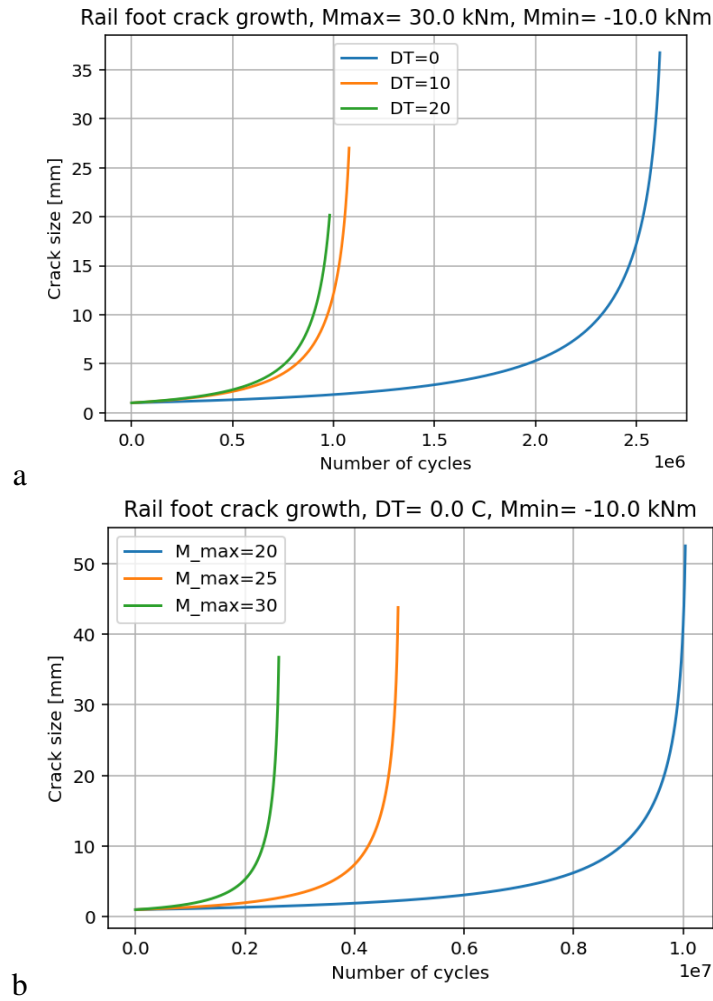


Figure 11: Growth of a trough thickness rail foot edge crack in a 60E1 rail (see figure 1).
 a) at different ΔT -values ($M_{\max} = 30$ kNm), b) at different $M_{\max}$ ($\Delta T = 0$).

For the cases of constant load amplitudes shown in figure 11 numerical integration of crack propagation is much faster than cycle-by-cycle integration.

Variable amplitude loading implies that the wheel load varies during the operational life of the wheel. In practice this variation must be expressed as a load spectrum derived from wheel load measurements similar to what is done using data from an instrumented wheelset in [8]. For variable amplitude loading it is also possible to employ numerical integration by using an equivalent stress (essentially an exponential average, see [3]). However by such an approach the effect of seasonal variations in thermal stresses on crack growth rates will not be seen.

Figure 12 shows an analysis featuring growth under variable loading and seasonal temperature variations. As seen in figure 12a the equivalent stress approach does not capture the seasonal variations, nor the load variations due to the variation in load

between the different wheel passages which are visible in the zoom-in in figure 12b.

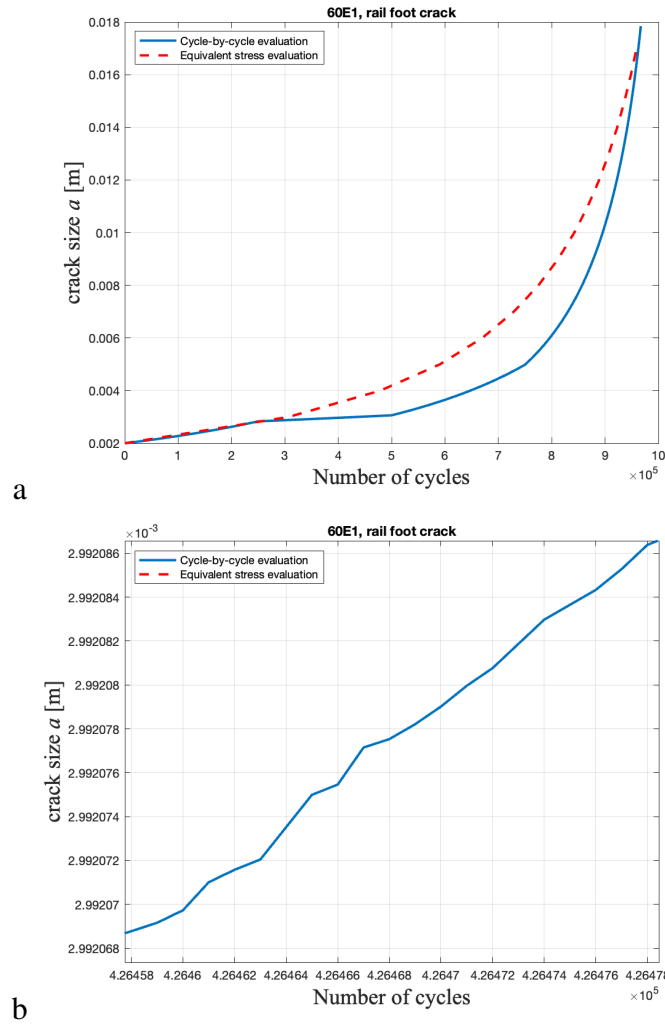


Figure 12: Growth of a trough thickness rail foot edge crack in a 60E1 rail at variable $M_{\max}$ magnitudes and seasonal temperature variations.

a) Overview comparison of numerical and cycle-by-cycle integration, b) Zoom-in on cycle-by-cycle integration results.

7 Concluding remarks

For rail cracks, methods exist to predict crack growth and (risk of) failure (based on detector data). The main challenge is to decide how ‘fine grained’ this analysis should be, and to obtain the required (input and model) data. This also relates to which uncertainties in input data and predictive models that are deemed acceptable.

For rail crack growth, single overloads are of less importance. From the point of view of causing a (dangerous) rail break, a difference in peak load of some 50 to 100 kN does not make a massive difference. However, since limits need to be fixed and

will have operational consequences, the precision of the load detector still needs to be high from a 'legal perspective'.

The same reservations also relate to sleeper damage. Here it is complicated to establish limit loads since the risk of sleeper cracking is highly dependent on the support conditions of the sleeper.

Settlements and flange climbing both relate more to the quasi-static load and to local track (geometry) faults.

Uncertainties in detector measurements can be divided into stochastic and systematic deviations, and deviations related to impact characteristics. In combination, these induce significant deviations in measured load magnitudes between detectors for a certain wheel flat at similar operating conditions.

To decrease this scatter, it is proposed to aim at eliminating systematic and stochastic deviations as far as possible. To reduce deviations caused by impact load characteristics would likely require analysis of wheel load histories (over detector passages, and during a passage), and possibly data from additional detectors in curves and/or wheel profile measurements.

As a basis for wheel damage classifications, a list of wheel tread damage types has been compiled with information about detectability, means of classification, influence on the track, risk of causing exceedance of load limits, and suitability to assess current status through wheel load detector data.

This list is used as a background for a discussion on recommended procedures. These recommendations are compiled in a table that outlines current potential of detection by wheel load detectors, increased potential with the ability to analyse wheel load histories, potential benefits of detectors in curves, and additional benefits of obtaining wheel profile data. A strategy is proposed where extensions to current detector measurements are gradually introduced starting with collection of load history data. The extensions are proposed to be evaluated in simulations before implemented in operations.

Finally, an example is presented on how detector data can be employed for predictive purposes in an operational scenario. The example concerns growth and fracture of rail cracks. The example demonstrates pieces of an analysis framework that exist, and how they can be combined. What is required for wider implementation is the compilation of a coherent and comprehensive analysis framework based on existing parts. Further, decisions, strategies, procedures, and routines to collect and evaluate data are needed. To make such an implementation manageable, an incremental extension of the prediction framework is proposed.

Acknowledgements

This study is part of the activities within international centre of excellence CHARMEC, www.chalmers.se/charmec. This research was funded by Vinnova [2023-01218].

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