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# Lessons learned from data analytics, applied to the track maintenance of the Dutch high speed line

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ABSTRACT Life cycle performance and risk management are often mentioned as critical tasks for infrastructure managers. However, without proper data collection and analytics these tasks cannot be executed. This paper discusses lessons learned from a case where a data analytics approach was deployed when an unexpected phenomenon occurred on the Dutch High Speed Line (HSL-Zuid). In November 2014, it was found that large sections of the HSL-Zuid were affected by a severe type of rolling contact fatigue (RCF). The RCF resulted in deep cracks on top of the rail. These damages were unexpected as the rails were only 5 years in operation and these rails were expected to last about 20–25 years with proper maintenance. In this case, resulting in about 20 km of rail replacements and multiple additional grinding campaigns. As the causes of defects were unknown, the authors applied data analytics to evaluate the possible causes of the RCF. Several measurements of the infrastructure, maintenance and the rolling stock resulted in a set of parameters. Then, a bottom-up approach is proposed for evaluating the affected sections to find similar parameter values among these over the whole track. The idea was to look for parameter values which could explain why certain sections were affected by the defects while others were not. The outcomes of the analysis indicated that it is highly likely that one type of rolling stock was affecting the rails in the curves of the HSL-Zuid. As the track was designed at the high-speed sections for 220–300 km/h and this type of rolling stock was driving below design speed, different loading of the rails throughout the curves occurred. Lessons learned from this case do not only apply to the technical area of wheel/rail and vehicle/infrastructure interfacing, but also to the usage of data analytics itself and life cycle management. From this case study, it is discussed how data collection and analytics can be better embedded by (rail) infrastructure managers from an early stage of development and use of infrastructure. Further scientific development for infrastructure data analytics are also discussed.

## 1 INTRODUCTION

Railway infrastructure managers have different strategies for rail maintenance. Reactive/corrective approaches rely on various measurements and inspections which reflect the condition of the assets, so-called condition monitoring. When the condition reaches a certain level of degradation, the proper maintenance action is applied, whenever it is (cost) effective. Another approach is preventive maintenance. In order to use this approach effectively its necessary to know how fast the rail condition is degrading and whether the rail (section) is affected by rolling contact fatigue (RCF). Both maintenance approaches are often applied together in a rail managementc programme.

To perform condition monitoring and maintenance, rail infrastructure managers collect different kinds of data to measure the performance of their assets. However, the main triggers or cause of the degradation are not always known in advance. Moreover, rail infrastructure is complex, especially when dealing with interfaces between different components. For instance, the interaction between infrastructure and rolling stock. It is in the wheel-rail interface where the degradation process of the tracks occurs and more particular the degradation of rails.

In this paper, an integral methodology is presented, using data from both rolling stock and infrastructure. This has been combined into a bottom-up approach to evaluate the possible causes of the degradation of rails, looking for relevant parameter values within clusters (groups) of degraded tracks. The case study of the Dutch high-speed line (HSL-Zuid) is used to showcase the methodology. The focus is on the rail condition. Conclusions and lessons learned will be later discussed.

### 1.1 *Rolling contact fatigue*

Rolling contact fatigue is an issue related to the stress-cycle between wheel and rail which can result in rail defects (Dollevoet, 2010). Nowadays the most common rail defects on passenger lines are head-checks, squats and various forms of corrugation. Each of these defects have their own initiation mechanisms. The severity of defects is reflected by the number of defects (area affected) and the depth and length of the crack into the rails.

Defects can compromise the integrity of the rails. Without proper maintenance - in worst case, this can even result in the breaking of the rails. For head checks, the cracks appear at the gauge corner of the rails, mostly in curves with radii smaller than 3000 m and are most common on the outer rail of a curve (Dollevoet, 2010). Conditions which are considered to be critical for the initiation of head checks are high loading and friction, as reported in (Lewis & Olofsson, 2009). Squats appear on the top of the rails on the running band and are found on both straight track and large curves (Li, 2009). Squats have been reported in (Li, Zhao, Esveld, Dollevoet, & Molodova, 2008) to be associated with the occurrence of rail surface irregularities like: indentations, wheel burns and short-pitch corrugation. Early stage squats might not have cracks. However, the evolution of squats over time includes the development of cracks from the surface, especially severe in late stage squats.

### 1.2 *Measuring rail defects*

Cracks in the rails can be monitored by using techniques like ultrasonic or eddy current measurements. Ultrasonic measurements usually are employed to evaluate the condition of the rails as a whole. A beam of ultrasonic energy is sent into the rail, and transducers detect the return of reflected or scattered energy. The difference in time and amplitude of the reflections are processed to evaluate the condition of the rail (Clark, 2004). However, ultrasonic measurements have not proven accurate for early detection of defects as it measures only defects 4 mm from the rail surface (Popović, Lazarević, Brajović, & Vilotijević, 2015).

Eddy current measurements work with probes and electromagnetic induction and are able to detect surface defects like head checks, belgrospis, wheel burns and corrugation (Pohl, Erhard, Montag, Thomas, & Wüstenberg, 2004). They can accurately measure crack depths between 0.3 and 5 mm, thus suitable for early crack detection. Inspections can be done by both vehicles and hand measurements.

### 1.3 *Maintenance of rails*

The removal of rail defects can be done in various ways. Replacement of rails is in general the most drastic and costly measure. Replacement is usually expected to be done by the rail-infrastructure manager near the end of its service life. Either, because the rails have been worn out or when its more cost effective to replace them instead of applying other maintenance actions. Renewal of large rail sections can benefit track quality, as rails are one component within a track system.

Other type of rail maintenance is grinding using rotating stones and high-speed grinding machines. Grinding is used for preventive and corrective rail maintenance. Other types of rail maintenance are: planing, milling and grinding using oscillating stones. Grinding using rotating stones can be used for both corrective- and preventive maintenance. This method is effective to remove surface defects and retaining the desired rail profile (Magel & Kalousek, 2002). The rotating stone grinding is done by rail vehicles which carry multiple grinding stones each covering a part of the rail profile. The desired specifications can be achieved by adjusting the quality of the stones, the number of stones, speeds and the number of runs. Highspeed grinding is a method based on high running speeds of up to 100 km/h. The main advantage is that grinding can be done without much track possessions. Its main purpose is preventive grinding regarding RCF, corrugation and to keep reasonable acoustic values. The method is based on circumferential grinding, where the grinding stones are hydraulically pressed on the rails and passively propelled.

## 2 CASE HSL-ZUID

The HSL-Zuid is one of the latest additions to the Dutch railway network and the first high-speed passenger line of the country. The line consists of two parts of about 50 km double track, the first part runs from Schiphol Amsterdam airport to Rotterdam and the second part from Rotterdam to the Belgian border with switches halfway to the city of Breda. From the Belgian border the track continues to Antwerp in Belgium. An overview of the track is shown in Figure 1.

The HSL-Zuid was opened for commercial use in 2009. The highspeed sections of the track have been designed for a speed range of 220–300 km/h. Three types of commercial trains have been running on the track since it has opened for commercial services, two types of high-speed trains with speeds of up to 300 km/h and 250 km/h and a train with a conventional maximum speed of up to 160 km/h. However, the train with a maximum speed of 250 km/h was only used in commercial service for one month at the HSL-Zuid and was replaced by the conventional train due to technical difficulties in January 2012. The conventional trains are scheduled as of 2017 33 times a day whereas the high-speed is scheduled 14 times a day, in both directions. Both trains use the north track of the HSL-Zuid. On the south track however, the high-speed train

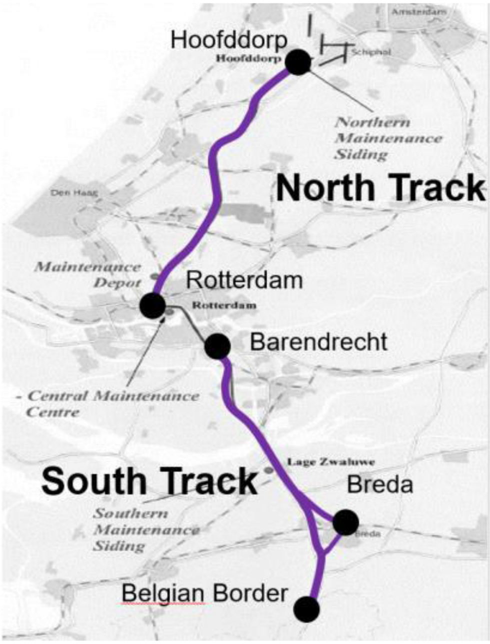



Figure 1. Overview of the HSL-Zuid (Schalk, 2016).

Figure 2. Picture of the examined damaged of the HSL-Zuid. The cracks do not grow into the rail but stay relatively close to the surface (Schalk, 2016).

goes straight to Belgium whereas the conventional train is scheduled between Breda and Rotterdam.

The condition of the rail infrastructure was measured regularly by both eddy current measuring the gauge corners of the rails, inspecting it for possible head checks. Also, regular ultrasonic measurements were performed, checking the integrity of the rails as a whole. Also regular visual and camera inspections were performed in order to assess the condition of the track.

During a visual inspection along the track in November 2014, some severe damages in the form of cracks in the rails were found. These were not detected by the regular measurements. These findings indicated that the monitoring programme was not sufficient as it did not detect these cracks in an early stage and the monitoring programme seemed therefore not tailored for the requirements of the HSL-Zuid. Also these serious defects occurred after only a few years of commercial operation of the HSL-Zuid with very low service usage. These findings resulted in a large track inspection where additional areas were found with the same kind of defects, so-called hotspots. Pieces of the rails were taken out for further investigation, which concluded that the rails themselves were according specifications and without irregularities, ruling out fabrication errors. A picture of a piece of damaged rail is shown in Figure 2.

Also, the defects were classified by experts as studs. These show similarities with squats in their external appearance. However, the cracks do not grow deep into the rail but often grow towards the gauge corner of the rail (Stuart L Grassie, Fletcher, Hernandez, & Summers, 2011). Also well developed studs can result in spalling out (S.L. Grassie, 2015). These defects at the HSL-Zuid only were found at the (harder) heat treated 350HT rails which are located only among the curves of the track. The straight track among the HSL has a softer 260 rail grade. According to (Wilson, Kerr, Marich, & Kaewunruen, 2012) from Australian experiences, studs indeed seem to be more prevalent on harder rail grades than softer ones. Their occurrence described in (S.L. Grassie, 2012) shows that hotspots of studs often occurred in track sections related to high tractive efforts and that they were only occurring in open areas, which can be linked to the need of moisture in order for the defects to grow. Also, as the track was relatively lightly loaded (<30 MGT since the start of operations), it was unexpected that such damages could occur. (Steenbergen, 2016) shows that these defects can indeed occur very early in the assets' lifecycle with cumulative loading of the rails from 15 MGT.

The damages found had severe effects on the rail infrastructure as they were well-developed (up to 5 mm of depth). This resulted in the deployment of additional unforeseen grinding campaigns to remove the cracks and about 20 kms of rail renewals, 20 years earlier than the expected assets lifecycle.

## 3 METHODOLOGY

A bottom-up approach is next presented, which is based on data from both rolling stock, track infrastructure and maintenance. This data is shown in (sets of) parameters representing the track infrastructure and types of rolling stock, together with the condition of the asset assessed (rails). The approach is suitable for evaluating a whole network, track or track section. The rail condition is approached as the interaction between sets of maintenance-, track infrastructure- and rolling stock parameters as shown in Figure 3. The processed parameters have been chosen based on relevance according to literature regarding the occurrence of

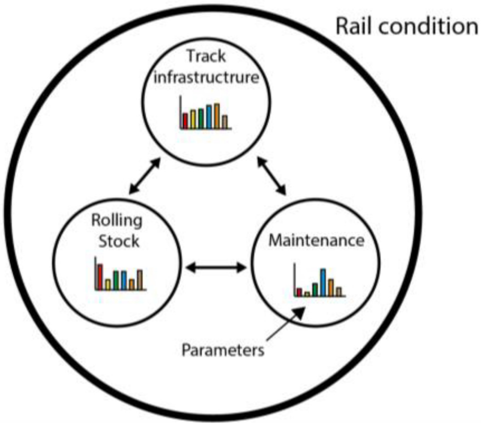



Figure 3. The approach is based on the principle of the rail condition being the result of the interaction between sets of parameters of track infrastructure, rolling stock and maintenance (Schalk, 2016).

Table 1. Overview of processed parameters.

| Track infrastructure | Rolling stock | Maintenance |
|---|---|---|
| Superstructure (type) | Cant deficiency (mm) | Grinding (type) |
| Rail grade (type) | Traction (%) | Grinding depth (mm) |
| Assets (type) | Speed (km/h) | Eddy current data (intensity) |
| Design speed (km/h) | Cumulative tonnage (MGT) | |
| Curve radius (m) | Tonnage per vehicle (MGT) | |
| Cant (mm) | | |
| Height difference (m) | | |
| Rail profile (type) | | |

RCF and availability of the data for the rail infrastructure manager. The processed parameters are shown in Table 1.

The approach is designed to find influencing parameters regarding the state of the rails. The damaged areas will be identified, using a KPI (key performance indicator) for the condition of the rails. These damaged areas (hotspots) are then evaluated regarding their respective set of parameter values. This principle is shown in Figure 4.

### 3.1 *Design of a KPI for rail condition monitoring*

To be able to evaluate the rail condition as the performance of a numerical parameter, a KPI is introduced. This KPI is based on the eddy current measurements, as these, when covering all the surface of the rail, were are able to detect the defects. The KPI is called intensity ($I_X$) as it resembles both the number of defects in a track partition ($n_{cHr,X}$) and the size of these defects. The KPI aims at the showing hotspots when the values exceed a threshold.

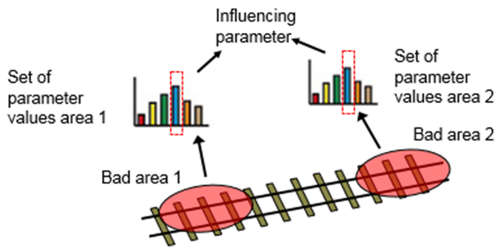



Figure 4. Visual representation of the bottom-up approach, which aims at evaluating the affected areas regarding their set parameter values.

Performance indicators regarding rail maintenance have been earlier reported in (Åhrén & Parida, 2009), (Stenström, Norrbin, Parida, & Kumar, 2016) and (Parida & Chattopadhyay, 2007). Processing measurements into a robust and predictive KPI considering the stochasticities of defects and predicting maintenance time horizons using ABA has been reported in (A. Jamshidi, Núñez, Dollevoet, & Li, 2016), (A. Jamshidi, Faghih-Roohi, et al., 2016) and (Ali Jamshidi, Núñez, Dollevoet, & Li, 2017). For the case study of the HSL-Zuid only one eddy current measurement of the whole track was available. This had been done using an Eddy Current Walking stick which covers the whole rail head. The intensity has been done for each leg separately. Categories ($c$) using thresholds for each mm of depth measured by eddy current and according category coefficients ($\lambda_c$) have been introduced. Cracks smaller than 0.1 mm have been removed from the measurements due to the accuracy. Intensity is being calculated as in (1), where $X$ is the interval position (partition) of the section located between $x$ to $x + 500\,m$ and $t$ the time of the measurement.

$$I_X(t) = \sum_{c=1}^{5} \lambda_c * n_{c,X}(t) \tag{1}$$

### 3.2 *Partitioning of the track*

The track will be divided in certain partitions ($X$). Each of these partitions will resemble the part of the track by their respective parameter values. In general the smaller the partitions the more accurate the resulting model will be, while bigger partitions will aggregate the results. In this case, we assume 500 m as a fixed size partitioning value. The proposed partitioning principle is shown in Figure 5.

### 3.3 *Processing of parameters*

The different signals from the parameters introduced require a strategy of processing into one model. Both quantitative and qualitative variables are processed differently. For the qualitative variables a "mixed" value has been introduced for when a transition point is

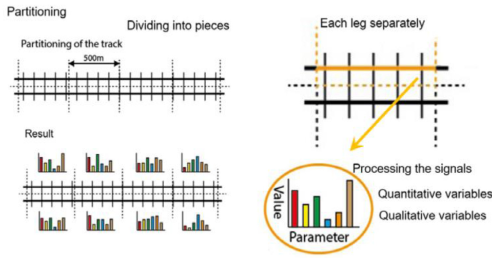



Figure 5. Partitioning principle (Schalk, 2016).

present in the partition. The method of processing these is thus non-homogenous where different signals can be presented in a single partition. An example regarding the parameter value for the rail grade in a partition is mathematically formulated as:

$$\delta_X^{rail}(k) = \begin{cases} 260 \text{ if } \delta^{rail}(x,k) = 260 \text{ for all } x \in X \\ 350HT \text{ if } \delta^{rail}(x,k) = 350HT \text{ for all } x \in X \\ mix \text{ if } \delta^{rail}(x_1,k) = 260, \delta^{rail}(x_2,k) = 350HT \end{cases} \quad (2)$$

for: $x_1 \neq x_2 \in X$. in which
$\delta^{rail}(k)$: value of the parameter ($\delta$) rail at moment of measurement
$X$: partition
$k$: moment of the measurement
$x$: location

For the quantitative parameters the average value of the different signals within the partition has been used, for the example of rolling stock type 1 ($RS_1$) this is formulated as:

$$\delta_X^{RS_1}(k) = \frac{1}{N_X^{RS_1}(k)} \sum_{x \in X} \delta^{RS_1}(x,k) \quad (3)$$

For: $\delta^{RS_1}(x, k) \neq null$, where $N_X(k)$ are the number of signals within partition $X$ at moment of measurement $k$.

### 3.4 *Similarity between parameter values*

Similarity is introduced to be able to identify parameter values ($\delta$) which are similar between the different hotspots ($X_h$) of RCF. These are parameters with the same values for the nominal parameters and closely values for the quantitative ones. This will function as a filter for parameters which prove according the methodology to be unrelated to the issue of RCF and can be used to identify threshold values for where the issue does occur. The similarity function (V) is formulated as:

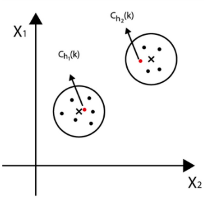
$$V\left(\delta_{X_{h1}}(k), \delta_{X_{h2}}(k)\right) = \left\|\delta_{X_{h1}}(k) - \delta_{X_{h2}}(k)\right\|^2 \quad (4)$$

The condition for similarity ($\varepsilon_\delta$) is formulated according a similarity threshold:

If $\delta_{X_{h1}}(k), \delta_{X_{h2}}(k)) \leq \varepsilon_\delta$ we will say: $\delta_{X_{h1}}(k) \approx \delta_{X_{h2}}(k)$ thus similar.

### 3.5 *Clustering parameters to identify hotspots types*

Regarding the similarities it can be the case that all hotspots share a similar parameter value for one parameter. This will be defined as a characteristic parameter value. However, to be able to distinguish different mechanisms causing RCF its not obvious that one set of characteristic parameter values will cover all hotspots, therefore unsupervised clustering is used. In order to achieve effective clustering these have to be homogenous and well separated (Hansen & Jaumard, 1997). Clusters consist of a group of similar parameters values for a certain hotspot type. The typical hotspot type can be selected as the centre of the cluster with the cluster definition (5).




$$\overline{C_{h_1}}(k) = \begin{bmatrix} \delta_{h_1}^1 \\ \vdots \\ \delta_{h_1}^m \end{bmatrix} \qquad \overline{C_{h_2}}(k) = \begin{bmatrix} \delta_{h_2}^1 \\ \vdots \\ \delta_{h_2}^m \end{bmatrix}$$

$$C_i(k) \in C_{h_1} \text{if } V(\overline{C_{h_1}}(k), C_i(k)) \leq \varepsilon_c \quad (5)$$

When the hotspots are evaluated, the output can for instance be that two hotspots types are found which divide the hotspots. This can be formulated mathematically as:

$$C_{h_1}(k) = \{C_2(k), C_3(k)\} \quad (6)$$
$$C_{h_2}(k) = \{C_1(k), C_4(k), C_5(k)\}$$

where $C_{h1}(k)$ is the selection of characteristic parameter values which are similar for a certain hotspot type $h_1$ at moment of measurement ($k$). Eventually the resulting parameter values for the clusters will be evaluated and checked whether they can explain the appearance of RCF at the evaluated track.

## 4 RESULTS

### 4.1 *Intensity*

Intensities are shown in Figure 6 and Figure 7. First the intensity is shown and then the intensity with a 3 mm threshold. Note that there is one peak remaining but with a far greater score for the left leg than the right leg.

The position of the peak shows one of the hotspots at the HSL-Zuid. Visual inspections also showed this was the worst affected section among the North-East track. The difference in how each leg is affected will explained by curve located in this track section. Among the HSL-Zuid a total of five hotspots were found varying in lengths between 800–5000 m.

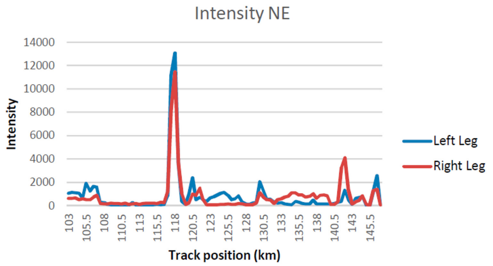



Figure 6. Intensity distribution for the North-East track of the HSL-Zuid (Schalk, 2016).

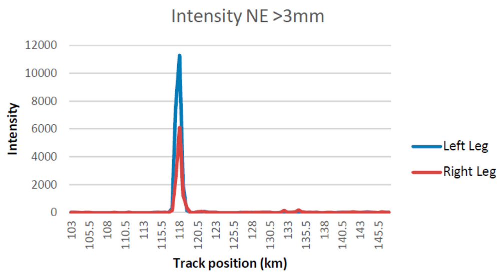



Figure 7. Intensity distribution for the North-East track of the HSL-Zuid with a threshold of 3 mm (Schalk, 2016).

### 4.2 *Similarities*

The most important similarities which have been found between the hotspots are:

– 350HT Rail grade.
– Location among curves with a cant of at least 75 mm.
– Anti head-check profile 60E2 in the upper leg of the curves (which is related to the curves).
– Dominant load comes from one type of rolling stock (conventional train)
– The same type of rolling stock has a speed lower than the design speed among all the hotspots of at least 30 km/h
– All hotspots lie in open areas (there are no damages in tunnels)

### 4.3 *Clusters*

The clustering resulted into two types of hotspots. The different speed profiles of both types of rolling stock resulted in being able to distinguish these two types of hotspots/clusters.

The first type of hotspot was called the 'open track hotspot':

– Located among the maximum speed area with a design speed range of 220–300 km/h.
– Cant excess for the slower type of rolling stock of at least 50 (at max 110).
– Traction present from both vehicles.

The second type of hotspot was called the 'entry zone hotspot', which can be characterized by:

– Design speed of 160 km/h.
– The slower type of traffic having a cant excess/deficiency of around 0.
– No traction present because they are located around a voltage lock.
– Located among S-curves.

Remarkable among these findings was that there were no hotspots in the track which is only being used by the high-speed type of train. Also, one of the entry zone hotspots is only being used by the slower type of train.

#### 4.3.1 *Hypothesis*

The hypothesis for the HSL focusses on the similarities which had been found and the two cluster types. Especially the relation between the parameters which could have an influence on the occurrence of RCF had been studied more closely.

For the HSL there seems to be a problem regarding the slow running type of rolling stock which contributes to roughly 70% of the total traffic for the track. The slow running traffic results in large cant excesses through the curves where the open track hotspots are located and driving within the theoretical cant value for the entry zone hotspots. Additionally the slow running train has larger tractive efforts, 75 kN per axle whereas the high-speed train has 56,25 kN per axle. Also the cracks solely occurring on the curves with the head-hardened rails installed was remarkable.

To check the results, whether these parameters were indeed influential regarding the occurrence for the HSL or not, additional tests were conducted. For the 'open track' hotspots, all curves which had cant excess larger than 50 mm had been studied. Which resulted in examining 13 additional curves. Among these curves were 2 curves with a 260 rail grade and tractive efforts from both trains were present, thus all characteristics for an open track hotspot were available except the rail grade. These curves were unaffected by RCF, seemingly the 350HT rail grade combined with the slower running traffic results in cracks growing faster than wearing out. For the 260 rail grade results in cracks wearing out rather than growing. Among the other curves five also shared all the same characteristics. Four out of these also had larger concentrations of RCF based on eddy current. However, damages were not as severe to exceed the set thresholds or the curves didn't meet the length criterion. For the entry zone hotspots the same procedure has been followed. Here the slow driving speeds result in theoretical cant through the curves. Which can cause unpredictable behaviour due to having no leading leg through the curves thus no resultant for the lateral acceleration along the curves. Here, there were no other areas sharing the same characteristics. Two other entry zones were located in tunnels whereas another entry zone is located at the Belgian border where only the faster train uses the tracks and comes in at maximum speed.

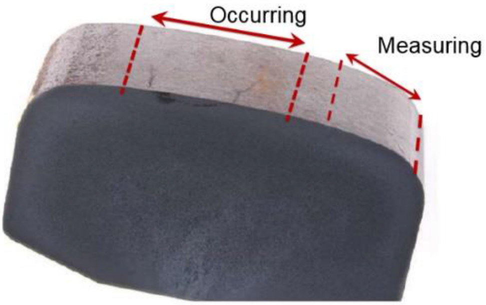



Figure 8. The mismatch shown between the eddy current measuring and the occurrence of the cracks (Schalk, 2016).

## 5 CONCLUSIONS

The rail infrastructure and vehicle interaction works as a system. Often, high-speed traffic is considered to be more critical for the infrastructure. The results of this case indicate it can also work the other way around, where high-speed infra is being used by rolling stock with conventional speeds. The different track loading among the curves seem to affect the rails, while the effects on the rolling stock are yet unknown. At first instance the rail infrastructure manager thought the new rolling stock should have a positive effect on the expected lifespan of the rails as the annual loading was much less than expected during design.

In order to apply an integral maintenance strategy, considering the track-vehicle interaction as a system is critical for a cost-effective strategy over the life cycle of the system. It has proven essential from a rail infrastructure managers perspective to have also the data available from rolling stock. Traction values, speed profiles and the loading (total number of MGT's) of the different kinds of rolling stock. This is needed in order to be able to see how each track section is loaded. By evaluating the effects from both types of rolling stock, this can support decision making for maintenance for different track sections.

In the studied case the maintenance was heavily dependent on monitoring by measurements. Whereas in the new situation the rails were loaded differently. The monitoring of early defects was still focussed on the gauge corner of the rails, thought to be the most critical rail surface area regarding the potential development of head-checks. While in the new situation, more trains with conventional speeds are using the track and now the lower rail in curves and the rail head was more loaded. This should be further investigated as it could be the cause of these defects. The mismatch between the measuring by eddy current – early crack detection and the occurrence of the defects is shown in Figure 8.

When new vehicles with very different specifications are commissioned on the track, an integral approach should be considered looking at the effects for both the rolling stock, infrastructure and the maintenance/monitoring. Looking for the changes compared to the current train track system.

The approach is heavily dependent on the availability and quality of the data for the rail infrastructure manager. At the HSL-Zuid the infrastructure manager already had all track data bundled in a central IRISsys database, which helped analysing and processing of this data. However, measuring more parameters should be helpful. For instance, measurements of the actual forces at the wheel-rail interface could provide proof for the actual cause of damages.

Expanding the model with more eddy current measurements could enable to tool to be more helpful for the rail infrastructure manager as trends in the intensity could be studied. This can be very helpful setting optimal maintenance and monitoring intervals.

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