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Data Analytics for the of RCF Damages on the Dutch High Speed Line

Ricks SCHALK[1], Alfredo NUNEZ VICENCIO[2], Arjen ZOETEMAN[1] and Rogier WOLFERT[1]
[1] *Integral design and Maintenance, Delft University of Technology, Delft 2628CN, The Netherlands.*
[2] *Railway Engineering, Delft University of Technology, Delft 2628CN, The Netherlands.*
**Corresponding author email: A.A.NunezVicencio@tudelft.nl*

Abstract: During a typical measurement campaign, lots of temporal and spatial data can be gathered regarding the condition of the rail. This paper proposes two approaches that make use of data analytics techniques to find causes of rolling contact fatigue (RCF) damages. The first approach, named 'bottom-up approach', determines the influencing factors regarding RCF based on the worst affected areas (hotspots). The second approach, called 'top-down approach', determines the influencing factors based on the condition of the whole track. The approaches use correlation analysis, clustering and similarity of parameters. To show the advantage of the approaches, they have been used for the study of the Dutch High Speed Line (HSL). The results indicates that severe RCF defects occurred only under two very specific conditions. First, in specific curves where one type of train was driving under high tractive efforts and large cant excess through curves. Second, at the entry zones of the HSL where voltage locks are present, the same type of trains' low driving speeds result in driving without cant excess/deficiency (theoretical cant). The conditions suggest that structurally driving below design speed on a high-speed track can be a cause of rail damages.

Keywords: Rolling contact fatigue; Data analytics; Rail measurements, High-speed rail

1 Introduction

Railway infrastructure maintenance companies have to deal with several issues in order to keep the rails in a good condition. One of these key issues is the problem of rolling contact fatigue (RCF). Every cycle of a wheel results in a stresses for both wheel and rail, which together to other factors, eventually lead to fatigue during its lifetime (Dollevoet, 2010). In severe stage, the fatigue can be visible with cracks in the rails, and eventually can lead into rail breaks if no corrective maintenance is taken. Therefore, it is mandatory for the railway infrastructure maintenance companies to keep control of the rail condition, and to detect early cracks that can be effectively treated before they grow into serious defects.

In some tracks, a separation of the different kind of rolling stocks is not possible. Thus, the same infrastructure is shared by conventional trains, high-speed passenger trains, and in some cases together with freight traffic. Different types of rolling stock cause different rail-vehicle interaction. In order to understand the contribution of each type of rolling stock to the appearance of RCF, it is crucial to understand the relevant parameters of the infrastructure, looking at the system as a whole. Moreover, railway tracks are distributed parameters systems, meaning that they change over location and time. For instance, different kind of rail grades or superstructure are used at different locations.

In this paper, the combination of two approaches is proposed to determine the influence of different parameters regarding the appearance of RCF. The methodology is based data analytics, which is nowadays a well-known tool to process big amount of data, both qualitative and quantitative, to obtain valuable insights about the relations between different complex parameters. The methodology can be used as a decision making support tool to ease the track maintenance decisions by monitoring the important changes in the track infrastructure, and also to suggest adaptations in the use of rolling stock for certain track locations. As case study, the approaches have been applied to the Dutch high-speed line (HSL) track.

The rest of this paper is divided as follows. First the background is introduced, including the case study, measurement techniques, RCF and rail maintenance. Then, two approaches are described. Next, the results of the application of the approaches are presented. Finally, conclusions and recommendations for further research are presented.

2 Background

2.1 The Dutch HSL-South

The HSL-South is currently the only high-speed track in the Netherlands. The construction of the track was finished in 2006 and was opened for commercial traffic in 2009. The track consists of two major parts of about 50km of double track, the first running from Rotterdam to Hoofddorp (Amsterdam) and the second one running from Barendrecht (Rotterdam) to the Belgian border with a turnout halfway to the Dutch city of Breda.

Two types of rolling stock are providing services over the HSL: a high-speed train with maximum speeds of 300km/h and a train at conventional speed of maximum 160km/h. Some general infrastructural characteristics are: two types of rail grades, 350HT for most curves, and the rest a standard carbon rail grade of 260. A 60E2 (anti head check) profile in the high rail of the curves. A slab track superstructure Rheda 2000. Ballast 160 and Ballast 300 at the transitional areas between the conventional Dutch track and the Belgian high-speed tracks. Canting up to 180mm in the curves, which has been designed at the maximum speed areas for a speed range of 220-300km/h. Also some special assets are to be found among the HSL like: a bridge, several tunnels, viaducts, flyovers and voltage locks.

2.2 Rolling contact fatigue

Rolling contact fatigue can appear in different forms. Especially defects like squats and head checks have been studied by different research groups. For this study the causes and appearance of three types of defects have been taken into account, namely: squats, studs (spalling defects) and head checks.

Squats are a type of defect which occurs on top of the rails, within the running band, most commonly on straight track and large curves (Li, 2009). The cracks are commonly U, V or Y shaped (Dollevoet, 2010). Squats are often associated with local stiffness variations and the occurrence of rail irregularities like indentations, wheel burns and short-pitch corrugation (Li et al., 2008a), (Li et al, 2008b). Other causes which are associated with the appearance of squats are white edging layers at the surface area of the rails (Carrol & Beynon, 2007) and high tractive efforts, in particular with high-speed traffic (Magel, 2011).

Head checks are located at the gauge corner of the rails. Generally, the distance between the cracks is between 0.5-0.7mm (Larsson-Kråik, 2009). Head checks are often found in curves with radii smaller than 3000m, mostly on the outer rail (Dollevoet, 2010). Head checks result from accumulation of ratcheting, which exhausts the ductility of the surface material where the first point cracks can initiate. The conditions which are considered to be critical for the appearance of head checks are high loading and friction (Lewis & Olofssun, 2009).

Studs or spalling defects have only been recently reported (Grassie et al., 2011), (Grassie, 2015) and (Grassie, 2012). They appear as a ‘V-shaped surface breaking crack whose apex pointed towards the field side of the rail’. Initiation occurs at the head of the rail, in ‘hotspots’, on both straight track and curves. Some of the hotspots were characterized by areas where trains approach signals and often have to brake or give traction. Studs also can grow very rapidly, compared to other surface defects. Australian experience with studs, reported by (Wilson et al., 2012), indicates that the occurrence of studs seems to be more prevalent in head-hardened rails than standard carbon rails. The cause of studs and the initiation mechanism is not yet fully understood, thermally transformed material had been found often together with studs, possibly caused by wheel-slip.

In November 2014, during a visual inspection walk along the tracks some severe unexpected damages were found at the rails of the HSL-South. The RCF found at the HSL-South seems to have most in common with the studs as reported by Grassie. Two material investigations have been done regarding the damages. The affected rails by RCF all have a head hardened rail grade, 350HT. White edging layer had been found in all the samples. The defects appeared in hotspots around curves in the HSL. Fig. 1 shows one material sample of the surface crack.

Fig. 1 Picture of one piece of examined rail from the Dutch HSL. The cracks stay relatively close to the rail surface

2.3 Maintenance and measuring

The HSL follows a condition based maintenance program, based on crack detection by ultrasonic- and eddy current measurements, together with visual and video-camera inspections. However, all the methods used were not sufficient to detect and measure the cracks from its early stage. The cracks were too small to penetrate deep enough through the material for ultrasonic detection. While eddy current measurements - suitable to detect early defects - were focusing on the gauge corner of the rails. Fig. 2 shows the mismatch regarding eddy current measurements at the HSL.

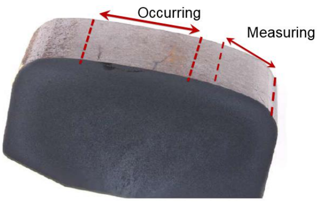


Fig. 2 Mismatch regarding eddy current measurements and appearance of surface cracks

The unexpected finding of the surface defects caused the infrastructure maintenance company to introduce a new measurement technique based on Sperry's eddy current walking stick. This measurement was able to cover the whole rail surface. The whole track has been measured using this new technique, resulting in the finding of other severely affected areas, causing additional grinding operations and large rail renewal operations after only 6 years of service.

3 New Methodology

The findings of the severe RCF raised the question by the infrastructure maintenance company, what could have caused these severe damages after only six years of service and a total cumulative tonnage of only 30 MGT. To support the finding of influencing parameters causing RCF damage, two new approaches are proposed. The first based on studying the worst affected areas in a railway track, and the second based on correlation analysis for a whole track measurement.

The approaches can be used in a whole network, a given track or a partition of the track. The approaches are based on sets of parameters: maintenance, track geometry and rolling stock parameters, as the rail condition is the result of the interaction between them, as represented in Fig 3.

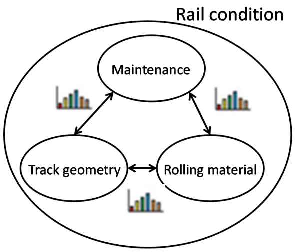


Fig. 3 The rail condition based on the interaction between different sets of parameters

The parameters proposed to process were selected based on the available data of different measurement campaigns and parameters which have proven influential regarding RCF according to the literature. The proposed parameters are listed in Table 1.

The analysis depends on the selected partitioning of the network. In general, the smaller the partition the more accurate the accumulated results will be. However, the processing of the data will be more intensive when smaller partitions are chosen. For the HSL partitions of 500m for each leg separately have been chosen.

Table 1 processed parameters

Track geometry	**Rolling stock**	**Maintenance**
Superstructure	Cant deficiency	Grinding type
Rail grade	Traction	Grinding depth
Assets	Speed	Eddy current data (intensity)
Design speed	Cumulative tonnage	
Curve radius	Tonnage per vehicle	
Cant		
Height difference		

3.1 Intensity: a KPI for rail condition

The definition of a good key performance indicator (KPI) is a challenge for railway systems. Regarding railways operations, those KPI's will govern the way the maintenance operations are managed. Key performance indicators have been reported in (Wilson et al, 2012), (Åhrén & Parida, 2009), (Parida & Chattopadhyay, 2007), (Stenström et al., 2016) and (Stenström et al., 2015). In order to value the rail condition, a new KPI has been designed, which resembles both the number of defects within a partition and the severity of the defects (crack depth). This new KPI called "intensity" relies on eddy current measurements. Detected cracks smaller than 0.10mm have been not considered due to the accuracy of the measurements. The categories with related coefficients for intensity an overview are shown in Table 2.

Table 2 Threshold values used in order to calculate intensity

Intensity category c	Coefficient category	Lower bound [mm]	Upper bound [mm]
1	1	0.10	0.99
2	2	1.00	1.99
3	3	2.00	2.99
4	4	3.00	3.99
5	5	4.00	4.99

For the calculation of the intensity values for a certain partition the following formula is introduced:

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

where I_X is the intensity at rail partition X, X is the interval position of length 500m, t is the time of measurement, c the category, λ_c is the category coefficient, $n_{c,X}(t)$ is the number of defects in category c at partition X at time t.

Also, more detailed intensity indexes can be introduced, for example only defects larger than 1.00mm or 3.00mm. An example of introducing a threshold for defects larger than 3.00mm is shown in the following formula (2):

$$I_X^3(t) = \sum_{c=4}^{5} \lambda_c n_{c,X}(t) \qquad (2)$$

in which I_X^3 is the intensity for defects larger than 3.00mm.

3.2 Bottom-up approach

The bottom-up approach aims to find the cause of the damages from already defined hotspots. The hotspots have been selected according four criteria: First, exceeding an intensity threshold, dependent on the partition length (smaller partitions – lower thresholds). Second, with visual evidence of the damages on the rails, by photo images. Third, the severity of the damages caused the maintenance company to do corrective grinding. And finally, a total length covering at least one whole partition of 500m. A schematic representation of the bottom-up approach is show in Fig. 4, which will be described stepwise.

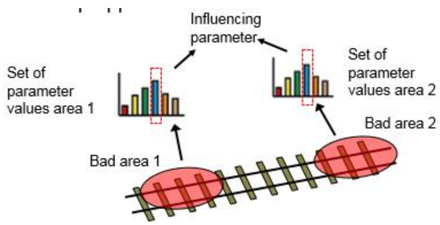


Fig. 4 Schematic representation of the bottom-up approach to find influencing parameters

In (Jamshidi et al., 2016a) and (Jamshidi et al., 2016b) the categories proposed cover longer crack depths on the defects, which is not allowed for the HSL. Also, the visual length of the squat defects is used. In the case of the HSL, the visual length was not available with photos, so new categories were defined to better adapt to the local conditions.

3.3 Processing parameters

Both, quantitative and qualitative parameters are considered. In case of qualitative parameter is not the same in whole partition, a new qualitative parameter "mix" is introduced. An example is shown for the rail grades according (3):

$$\delta_X^{rail}(k) = \begin{cases} 260 & \text{if} \quad \text{rail grade is 260, } \forall x \in X \\ 350HT & \text{if} \quad \text{rail grade is 350HT, } \forall x \in X \\ mix & \quad\quad otherwise \end{cases} \tag{3}$$

For the quantitative variables (speed, radius, cant, etc.) the average value of the different signals within the 500m partition has been used. This is formulated with the example of the speed of a vehicle as in (4):

$$\delta_X^{Vtraxx}(k) = \frac{\sum_{x \in X} \delta^{Vtraxx}(x,k)}{N_X^{Vtraxx}(k)} \tag{4}$$

for $\delta^{Vtraxx}(x,k)$ not null values of the speed of the TRAXX at moment of measurement k, location x and $N_X^{Vtraxx}(k)$ the number of data points in the signals within partition X at moment of measurement k.

3.4 Similarity

A next step in the processing is to find the similarity between the hotspot parameters. These are parameters that have the same values for the nominal parameters and have closely related values for the numerical ones. Hotspots are then compared to each other. This, in order to be able to detect relevant parameters which should be investigated with more details. The other argument would also to be able to exclude a number of parameters as the cause for the damages at the hotspots. Another opportunity that arises when comparing the parameter values, is to see how they relate and be able to compare numerical values for the parameters at the hotspots with other non-affected areas. The similarity function (5) is used to describe the similarity of one parameter at two hotspots:

$$V\left(\delta_{X_{h1}}(k), \delta_{X_{h2}}(k)\right) = \left\|\delta_{X_{h1}}(k) - \delta_{X_{h2}}(k)\right\|^2 \tag{5}$$

Where V is the similarity function, δ the parameter value, X_h the location of hotspot h, and k the moment of the measurement.

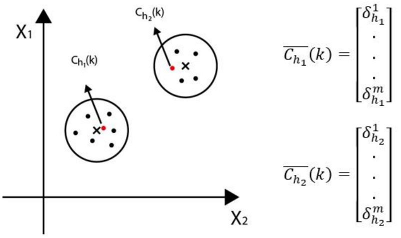
The condition for similarity will be described according a similarity threshold ε_δ :If $V\left(\delta_{X_{h1}}(k), \delta_{X_{h2}}(k)\right) \le \varepsilon_\delta$, we will say that $\delta_{X_{h1}}(k) \approx \delta_{X_{h2}}(k)$, thus the hotspots are similar with respect to the parameter δ .

3.5 Characterize hotspots using clustering

Regarding the similarities, it can be that all hotspots share for instance the same value for one parameter. This will then be defined as a characteristic parameter value. However, it is not obvious that one set of characteristic parameter values will cover all hotspots as there can be different mechanisms causing RCF at the railway track. Therefore, the technique of clustering will be introduced, which aims at distinguishing types of hotspots. Clustering is a measure of grouping, more specifically 'unsupervised classification' which aims at discovering groups in data (Govaert, 2009).

Regarding the clusters its required that the data is homogenous and well separated (Hansen & Jaumard, 1997). The sample for the clustering will be the set of hotspots which have been found earlier using the identification of the hotspots. The clusters will consist of sets of characteristic similar parameters for a certain hotspot type according to the center of the cluster and cluster definition, as shown in (6).

According the clustering defined, not every hotspot type will have an equal number of characteristic parameters. Also it is possible that the clusters are not well separated for every characteristic parameter because of having the same qualitative parameters.



$$C_i\left(k\right) \in C_{h1}\ if\ V\left(\bar{C}_{h1}\left(k\right), C_i\left(k\right)\right) \le \varepsilon_c \quad (6)$$

3.6 *Hypothesis*

The next step is to evaluate the types of hotspots which have been identified using the clustering. Here the values for the characteristic parameters for the hotspot type should be evaluated. During this evaluation the parameter values will be linked to the literature regarding RCF. This, in order to determine whether a single parameter or a set of parameters can be linked to causing RCF for these hotspots. According to this evaluation, a single parameter or a set of parameters can be used to establish hypotheses for the types of hotspots.

The last step will be checking the hypothesis. The hypothesis establishes conditions for the parts of the tracks vulnerable for damages. There are different possible outcomes which can be followed using the flow chart presented in Fig. 5.

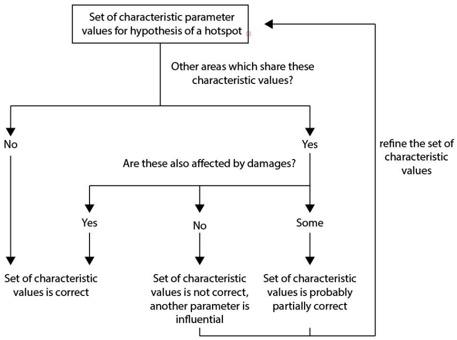


Fig. 5 Flow chart regarding the steps of the hypothesis checking

3.7 *Top down approach*

The aim of the top down approach is to analyze the whole rail condition of the system. The set of established parameters are used, in order to see how much each parameter relates to the condition of the rail. The intensity parameter is consider as the performance indicator; thus, it will be checked how it is influenced by the other parameters. A schematic representation of the top down approach is shown in Fig. 6.

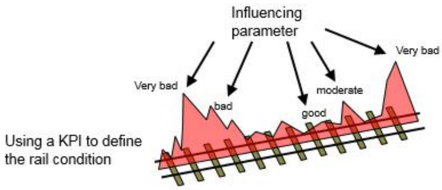


Fig. 6 Schematical representation of the top down approach

There are several data analysis techniques which can be used in order to evaluate numerical parameters. Using SPSS software enables to do simple statistical analysis among large data sets. Two considered options were linear regression analysis and correlation analysis. Both are much alike when it comes to identify a linear relation between two variables. The relationship between both can be formulated according (Rodgers & Nicewander, 1988):

$$r = b_{Y \cdot X}\left(\frac{S_X}{S_Y}\right) = b_{X \cdot Y}\left(\frac{S_Y}{S_X}\right) \quad (7)$$

where r is the Pearson's correlation coefficient and b_{XY} and b_{YX} are slopes (Lee Rodgers and Nicewander, 1988). Regarding the numerical results, the parameters will be evaluated using Pearson's correlation. Pearson's correlation can also be used to measure relations on an interval or ratio scale (Egghe & Rousseau, 1990). The original mathematical formula for correlation by Pearson for two variables is as follows:

$$r = \frac{\sum\left(X_i - \bar{X}\right)\left(Y_i - \bar{Y}\right)}{\left(\sum\left(X_i - \bar{X}\right)^2\left(Y_i - \bar{Y}\right)^2\right)^{1/2}} \quad (8)$$

This coefficient values range between -1 and 1, where -1 means that when one variable changes the other changes in the opposite direction by the same amount, while the value 1 means that when the first variable changes the other one changes by the same amount. A value 0 means the there is no relationship, when one variable changes the other doesn't change at all.

The other output value is the significance value, which is a p-value. The significance value gives a probability for getting the correlation value if the null hypothesis were to be true (thus no relation between the parameters) (Field, 2009). Significance criterions handled are usually 0.05 or 0.01, thus the lower the significance value the less likely the null hypothesis is true. Using the output of the parameters, the significant parameters can be ranked according to their p and r values, which tell which parameters influence the intensity most.

Correlation is not suitable to evaluate the relation between intensity and qualitative parameters. It is interesting to see how the values for the intensities are being distributed over different qualitative parameters. A suitable method for this is the use of comparative boxplots, which allows easy visual comparison between of the features of different sets (Navidi, 2010). The boxplot can show: the level, spread and symmetry of distribution of the data, using the median, first and third quartiles and the outliers in a sample (Williamson et al., 1989).

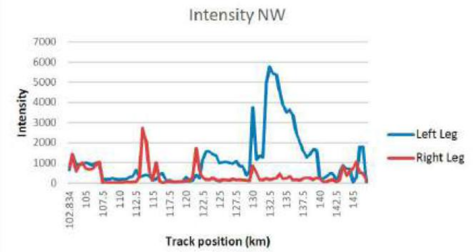


Fig. 7 intensity for the North-West track of the HSL

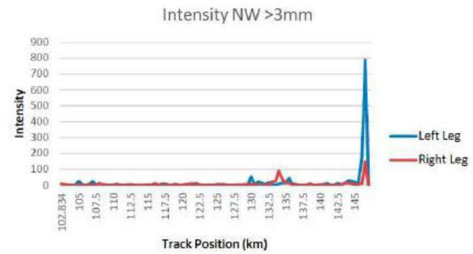


Fig. 8 intensity for RCF/surface cracks deeper than 3.00mm for the North-West track of the HSL

4 Results

An example, intensity is presented for the North-West track HSL in Fig. 7-8. The distribution of the intensities differs when applying the 3.00mm threshold. Initially, different peaks were present, but after only one large peak remains which is the worst affected area, a clear hotspot. In total four additional hotspots had been identified over the whole HSL with varying lengths between 800-5000m. Those hotpots are presented in Table 3.

4.1 *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 75mm, anti headcheck profile 60E2 in the upper leg of the curves, dominant load comes from one type of rolling stock, the same type of rolling stock has a speed lower than the design speed among the hotspots of at least 30km/h, all hotspots lie in open areas (no damage was found in tunnels)

Table 3 Overview of the hotspots and the hotspot criteria

	Zoetermeer NE 117.4-119.7	**Hoofddorp NW 145.9-147**	**Turnout G 300.5-301.3**	**SE 218-221**	**Rijpwetering 1 NW 130-135**	**Rijpwetering 2 NE 132.5-134**
Intensity^3 average	Yes 2418	Yes 189	Yes 60	Yes 321	No 17	No 38
Grinding	Yes 5,5mm	Yes 6,0mm	Yes 3,0mm	Yes 2,3mm	Yes 4,3mm	Yes 3,5mm
Visual evidence	Yes	Yes	No	Yes	Yes	Yes
Length	Yes 1.3km	Yes 1.1km	Yes 0.8km	Yes 3.0km	Yes 5.0km	Yes 1.5

4.2 *Clusters*

The clustering resulted into two types of hotspots. The different speed profiles of both types of rolling stock resulted in distinguishing the types of hotspots/clusters.

The first type of hotspot was named the ‘open track hotspot’: Located at the maximum speed area with a design speed range of 220-300km/h, cant excess for the slower type of rolling stock of at least 50 (at max 110), and traction present from both vehicles.

The second type of hotspot was named the ‘entry zone hotspot’, as they are at the entry zones of the HSL. It is characterised by: Design speed of 160km/h, the slower type of traffic having a cant excess/deficiency of around 0, no traction present because located around a voltage lock, and located among S-curves.

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

4.3 Hypothesis

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

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 in driving within the theoretical cant for the entry zone hotspots. Additionally the slow running train has larger tractive efforts, 75kN per axle whereas the high-speed train has 56,25kN per axle. Also the cracks solely occurring on the curves with the head-hardened rails installed was remarkable.

For the ‘open track’ hotspots, all curves which had cant excess larger than 50mm were studied. This resulted in examining 13 additional curves. Among these curves, 2 were curves with a 260 rail grade and tractive efforts from both trains. Thus, all characteristics for an open track hotspot were the same except the rail grade. These curves were unaffected by RCF, seemingly the 350HT rail grade combined with the slower running traffic result in cracks growing faster than wearing out. Among the other curves, five also shared all the same characteristics and four out of these also had larger concentrations of RCF based on eddy current measurement. However, damages were not as severe to exceed the set thresholds or the curves did not meet the length criterion.

For the entry zone hotspots the same procedure has been followed. In this case, the slow driving speeds result in theoretical cant through the curves. This can cause unpredictable behaviour due to having no leading leg through the curves; thus, no resultant for the lateral acceleration through the curves. Here the results were that 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.

4.4 Results top down approach

For the top down approach a number of situations have been evaluated. Using the results from the bottom up approach, the top down approach has been applied to check some of the results. Also to be able to rank the influencing parameters. For the analysis, two additional thresholds have been tested: cracks larger than 1.00mm and cracks larger than 3.00mm. The situations considered are:

- The whole track.
- Whole track without tunnels.
- Maximum speed track.
- Maximum speed track without tunnels.
- Entry zones.

The tunnels are not evaluated. Although traction and cant excess are present in tunnels, cracks of interest where just not present in this case.

The whole track, whole track without tunnels, maximum speed track and maximum speed track without tunnels all resulted in significant correlations with the tractive effort from the slower type of vehicle. Whereas significant correlations resemble significance at the 0.01 level. the open track without tunnels showed the strongest Pearson’s correlation coefficient and the whole track the least strong coefficient, though still significant relation with the intensity. Among these four areas, cracks larger than 1.00mm and also tractive efforts from the high-speed train also came out as significant; however, less strong than tractive efforts from the slower train. Curve related parameters did not come out significant in this analysis, which was unexpected. Seemingly, using the top down approach, tractive efforts are the dominant effects causing problems to the rail conditions.

5 Conclusions

In this paper, two approaches were proposed for analysing influencing factors to the appearance of RCF in the Dutch HSL. The bottom-up approach is more complex, as more steps are involved and it is greatly dependent on expert judgement about to interpreted the results. Whereas the top-down approach is applied with a relatively simple data analytics technique of Pearson’s correlation. Both approaches can work together by using finding from the bottom-up approach to determine the conditions to study, in order to be able to verify findings.

The applications are greatly dependent on the availability and quality of the data by the infra manager. For this research only one set of eddy current measurements was available. Using more measurements, also growth rates could have been processed and initial measurements being verified. Also, influences of grinding can be further studied when the depth of the grinding is recorded.

For this research fixed partition of the track have been used, which resulted for the qualitative parameters in mixed values when a transition point was present within the partition. Better results can be accumulated by using smaller partition sizes, though the processing of the data will be more intensive. Adaptive/variant sizes for the partitions can be developed when enough samples are available, and to remove the mixed values for the qualitative parameters.

Also, no maintenance data regarding the vehicles was available for this research. The availability of this would enable to expand the research regarding wheel maintenance/ conditions. KPI’s regarding the conditions of the wheels could be introduced as parameters to see whether these can be linked to the rail conditions.

For the HSL there has been a mismatch regarding the usage of the tracks and the actual maintenance program. The RCF was occurring at the head of the rails whereas the monitoring was focussed on the gauge corners. By upgrading the measurement system, covering the whole relevant areas, it will be possible in the future to avoid track renewals and to treat the cracks in an earlier stage.

According to the results for the Dutch HSL, one should consider removing the 350HT at the worst affected areas and replace them by a standard carbon rail grade. Moreover, the slower running type of train which is loading the track most, causes different behaviour regarding the wheel-rail interface. The slower speeds result in different behaviour through curves, which is shown in large cant excesses at the maximum speed areas and theoretical canting at the entry zones. This causes different stresses at the rail surface, likely to contribute to the fast growth and/or initiation of RCF. Further numerical simulations should be conducted to confirm this finding.

Further research is focus on trend analysis, predictive maintenance strategies, and big data analysis.

Acknowledgement

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