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Switch Panel wear loading – a parametric study regarding governing train operational factors

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ABSTRACT

The acting forces and resulting material degradation at the running surfaces of wheels and rail are determined by vehicle, track, interface and operational characteristics. To effectively manage the experienced wear, plastic deformation and crack development at wheels and rail, the interaction between vehicle and track demands a system approach both in maintenance and in design. This requires insight into the impact of train operational parameters on rail- and wheel degradation, in particular at switches and crossings due to the complex dynamic behaviour of a railway vehicle at a turnout. A parametric study was carried out by means of vehicle-track simulations within the VAMPIRE® multibody simulation software, performing a sensitivity analysis regarding operational factors and their impact on expected switch panel wear loading. Additionally, theoretical concepts were cross-checked with operational practices by means of a case study in response to a dramatic change in lateral rail wear development at specific switches in Dutch track. Data from train operation, track maintenance and track inspection were analysed, providing further insight into the operational dependencies. From the simulations performed in this study, it was found that switch rail lateral wear loading at the diverging route of a 1:9 type turnout is significantly influenced by the level of wheel–rail friction and to a lesser extent by the direction of travel (facing or trailing). The influence of other investigated parameters, being vehicle speed, traction, gauge widening and track layout is found to be small. Findings from the case study further confirm the simulation outcome. This research clearly demonstrates the contribution flange lubrication can have in preventing abnormal lateral wear at locations where the wheel–rail interface is heavily loaded.

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Dynamic train-turnout interaction; switch panel; wear; flange lubrication

1. Introduction

The increasing use of rail for both passenger and freight traffic is demanding a growing effort and cost of track maintenance and, if unchallenged, could become a major constraint in the development of overall railway productivity. Issues with track availability and cost related to maintenance will first present themselves at the more vulnerable bottlenecks in the railway network. From this viewpoint switches and crossings (S&C) clearly stand out,

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since a significant part of the annual rail infrastructure budget is already allocated to maintenance and renewal of S&C, illustrating its vulnerability. The Innotrack technical report [1] concludes 'switch wear' to be one of the top three main reported track problems.

S&C are important elements in the railway network operation, as they enable trains to change between tracks. Allowing trains to reach their targeted platform, the number of railway switches per route length is especially high at and around railway stations. A railway turnout consists of a switch panel and a crossing panel connected by a closure panel. The designated areas in turnout negotiation are indicated in Figure 1.

The high demand for maintenance at S&C is explained by the nature of its function, design and resulting forces. The dynamic behaviour of a railway vehicle in S&C is complex. From the switch toe (Figure 2), moving down the switch panel, switch- and stock rail profiles are gradually changing. This has an ongoing effect on the contact positions between wheel and rail, the acting rolling radius difference and resulting (tangentional) wheelset steering forces. When negotiating a switch in the diverging route, railway vehicles often experience significant lateral displacements. This will cause the wheel flange to come into contact with the rail face. When in flange contact, the level of lateral forces and high slip values can result in significant lateral rail head (side) wear, accumulated plastic strain and problems with crack formation and chipping of material (spalling). Due to the

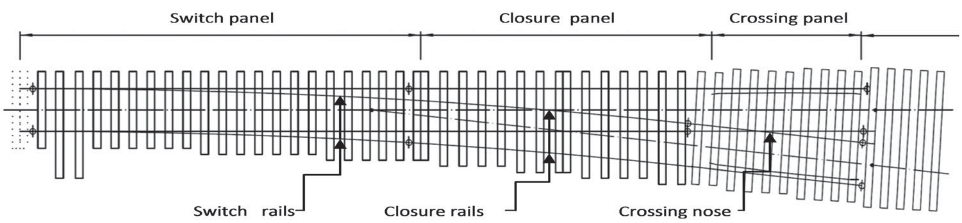

Figure 1. Designated areas in turnout negotiation.

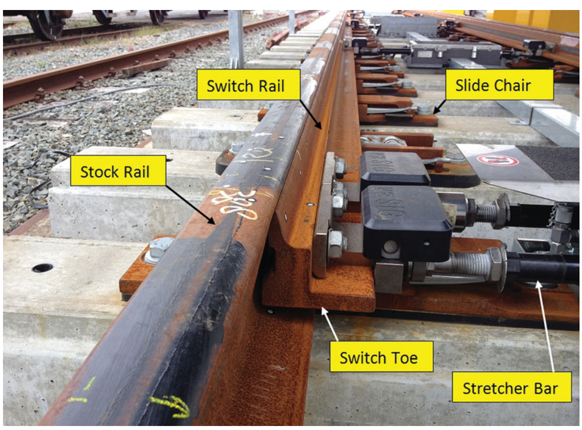

Figure 2. Switch panel components.

negative impact on service life and safety against derailment, severe side or gauge face wear of the switch rail will have significant operational and financial implications.

The Dutch railway network has around 8600 switches in its 7000 km of track. From [2], presenting the cost of operation and maintenance of track in the Netherlands, it can be seen that in 2014 yearly cost for S&C routine maintenance (KO), comprising inspection, service tests, small repairs and replacement of components, is about € 85 million covering 40% of the total annual KO track maintenance budget. Switch maintenance clearly claims a disproportionate amount of the overall budget. The in [1] reported Innotrack analysis of selected lines at Deutsche Bahn (DB) and Banverket (BV) identified the switch maintenance budget breakdown, presented in Figure 3.

Understanding the impact of individual train operational parameters on rail- and wheel degradation is required in order to manage the experienced wear, plastic deformation, crack development and resulting maintenance both at wheels and rail. To examine the effect of single parameter changes to resulting track loading and related material response, parametric studies can be carried out using commercial multi-body software like VAMPIRE® to model the dynamic interaction between vehicle and track/wheel and rail. Kassa and Johansson [3] present a parametric study for a Y25 freight bogie with respect to wheel profile, axle load and vehicle speed in relation to contact pressure and wear index along the switch rail at the diverging route. Especially for freight bogies, a large distribution in (worn) wheel profile shape and resulting multiple wheel–rail contact conditions are common as well as a large variation in axle load. Contact pressure and wear index were observed to increase with increasing axle load, the influence of train speed is however small, whereas the influence of wheel profile is significant. It is found that the large contact pressure on the switch rail was mainly due to poor contact geometry conditions. To further study, the influence of scatter in traffic parameters regarding the dynamic interaction between a railway freight vehicle and a turnout, Pålsson and Nielsen [4] performed a parametric study by simulations of vehicle dynamics. They showed that, when to account for wheel profile scatter, equivalent conicity is the wheel profile parameter best correlating to damage in the

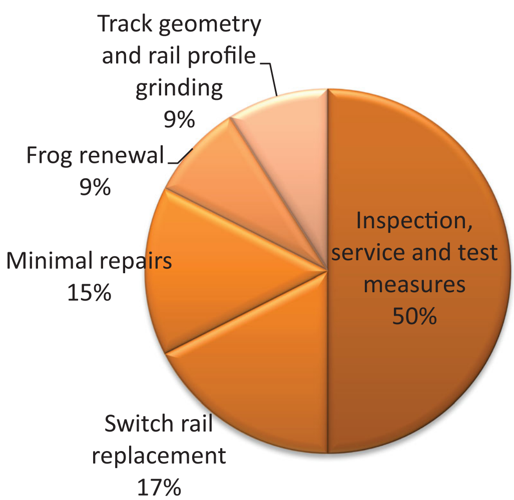

Figure 3. Switch maintenance budget breakdown [1].

switch panel. Beside the diverging route, side wear at the switch panel can also occur in the through route. Results of Spangenberg and Fröhling [5], evaluating severe side wear in a 1:20 turnout, conclude wear at the through route switch rail to be caused by rail profile changes in the switch area resulting in large lateral displacements of the wheelset. Further improvement of the switch panel design for the through route has been studied by Nicklisch et al. [6] and Bugarín et al. [7]. Based on a parametric study, dynamic track gauge optimisation by geometry gauge variation resulted, for the analysed configuration, in a significant reduction of wear and improved behaviour in terms of rolling contact fatigue (RCF).

Other train operational parameters potentially important regarding accumulated damage development, not included in [3], are e.g. direction of traffic, wheel–rail coefficient of friction, traction and mode of train operation (push vs. pull). The objective of the current work is to present a parametric study for the most common type of Dutch turnout (crossing angle 1:9), expanding the parametric scope to include further train operational parameters. However, not directly subject of this study, the effect of worn wheel or rail profiles and axle load is included into the discussion of this article. The level of wear loading at the rail surface resulting from trains negotiating railway turnouts in relation to train-track operational parameters is subject of this study. Additionally, a case study was performed, examining operating conditions at a location with reported severe switch rail wear and cross-checking the parametric study results. Following the specific track yard conditions, two track design parameters were added to the parametric study, examining the effect of track gauge widening and switches in short succession. The main goal of the presented study is to define the dominant switch rail wear influencing parameters in relation to train operation for the considered configuration. This understanding can further assist the track engineer in the optimisation of turnout performance.

The structure of this paper is as follows: after the introduction, Section 2 discusses different regimes of rail wear behaviour. Section 3 presents the modelling set up of vehicle-turnout dynamics. Section 4 presents how the simulation results are analysed regarding wear and fatigue behaviour. The main operational parameters are evaluated in Section 5, presenting the set up and results of the performed parametric study. Section 6 introduces the additional performed case study describing the nature of the occurring problem, documenting its circumstances and presenting results from data analysis and inspection. Overall findings are discussed in conjunction in Section 7 followed by conclusions in Section 8.

2. Rail wear

Due to the acting forces between wheel and rail, wear at the switch panel rail is generally to be expected. Earlier studies regarding the wear behaviour of wheel and rail materials identified different wear regimes, characterised in terms of wear rate and wear debris [8]. The three identified wear regimes were designated mild, severe and catastrophic. Also the occurring wear mechanisms within these regimes were investigated. At normal conditions the acting wear regime will be characterised as 'mild' with inter-metallic contact prevented by protective oxide layers [9]. The resulting wear rate is low, the contacting surfaces are smooth, without clear apparent wear debris. With changes to the system, for example, increasing wear loading or unfavourable material paring, a transition can occur from 'mild' to 'severe'. The wear regime is considered to be 'severe' when wear rates are high and roughness of the wearing surfaces is also high. Analysis of the contact conditions indicated that the transition from mild to severe was caused by the change from partial slip to full slip conditions [8]. A mechanism addressed as 'delamination wear' causes the severe wear regime at the wheel–rail contact, marked by deformation followed by crack growth and subsequent material removal. It is mainly generated by adhesion and metal to metal contact. Work from Johnson [10] shows delamination wear to be driven by the process of plastic strain accumulation known as ratchetting. The most evident sign of delamination wear is the existence of lamellar (plate-like) debris particles. Interestingly, the wear within this regime is found to be largely independent of sliding velocity, suggesting that it is controlled by contact stress and limiting traction alone. A second transition to catastrophic wear is considered to be the result of surface temperature effects. Assessment of material respond to cyclic stress can take place by using so-called shakedown maps, presenting the material hardening curves that define the areas with different types of material response. The shakedown map for a general three-dimensional rolling-sliding contact is presented by Ponter et al. [11]. The shakedown limit above which accumulation of plastic strain, that is, ratchetting will occur is seen to increase with decreasing friction coefficient. At coefficient of friction levels < 0.3, cumulative plastic flow occurs sub-surface. At friction coefficient levels > 0.3, plastic flow occurs dominantly at the surface. At relative high coefficients of friction (> 0.4), the ratchetting mechanism becomes very localised at the surface. Friction control through railhead lubrication, therefore can assist to move the operational point away from the area of ratchetting, relieving the surface. Other operational parameters addressing the shakedown load factor level and resulting material respond need to be further understood and quantified at an individual level. Damage models based on the calculated energy dissipation can be used for the evaluation of rail wear. This is further discussed in Section 4.

3. Modelling of vehicle-turnout dynamics

The wheel–rail contact is complex due to the relative motion of the two contacting bodies, elastic deformations and friction processes. To solve the contact problem, Kalker [12] developed numerical methods for rolling contact, making these available through his programme CONTACT and later the fast algorithm FASTSIM. Within vehicle system dynamics packages, multi-body software is used to describe both track and vehicles by a number of interconnected rigid or flexible bodies. System behaviour is obtained through analysis of the equations of motion, computing the dynamic movement of the different components, allowing the rail–wheel contact slip and locations to be determined. Then normal contact forces can be determined by for example, means of Herzian formulas and using FASTSIM for the tangential direction [13].

The use of dynamic simulation tools provides the railway engineer with the ability to quantify the impact of changes in design and operational parameters, by considering the complete interaction between vehicle and track. This work requires track and vehicle models to be set up, as well as operational inputs like speed and loading profiles. The simulation software VAMPIRE® Pro 6.30 has been used to simulate vehicle dynamics for traffic in the facing and diverging route. The used vehicle model is based on the Dutch VIRM-4 double deck passenger train, currently the largest proportion of the NS fleet. The model consists of a front coach with one leading trailer bogie and one motor bogie and an intermediate coach with trailer bogies, with a bogie spacing of 20 m. The wheel base is 2500 mm for the trailer and 2750 mm for the motor bogie. VIRM bogies are equipped with trailer arms, connecting the wheelset to the bogie frame. The trailer arm bushes determine the lateral, longitudinal and yaw primary suspension stiffness. The radial stiffness of the conventional primary suspension applied in VIRM trailing bogie is 30 kN/mm (linear behaviour) with resulting high primary yaw stiffness (PYS) of 60 MNm/radian. VIRM-4 trains are reported to suffer from fatigue crack initiation at the running surface (wheel rim). When allowed to grow, these cracks will lead to significant wheel diameter loss during wheel reprofiling aimed to remove these cracks. Therefore, since the year 2010 wheels of VIRM type trains are profiled about every 10 weeks to prevent development of initiating cracks. As a result, wheel profile variation of VIRM-trains is very limited, all very close to the applied design profile being UIC S1002 with reduced flange width. VIRM-4 vehicles have a maximum speed of 160 km/h and axle loads of up to 20 tons when fully loaded. At the axles of the motor bogie (axles 3 and 4), traction is simulated by applying a constant torque at both axles of 4.14 kNm, resulting in a driving force of 9 kN per wheelset. During VAMPIRE® simulation runs the vehicle speed remains constant. The vehicle model itself is connected to the rigid ground by a spring/damper. When a torque is applied to the wheels of the model, the driving force will be balanced by this spring/damper, preventing acceleration. Previously validation of the vehicle model has been performed, as described in [14]. Initially by comparing its resonance frequencies and natural damping coefficients with measured accelerations from a wedge test and further validated by comparing measured vehicle running behaviour with simulation output using measured track geometry data.

The multi-body model of the turnout is based upon a mass-spring–damper system. The track model consists of two rails, each attached to the rigid, massless sleeper by spring–damper elements in the lateral direction. The sleeper is connected with two vertical spring–damper elements to the rigid ground. The track model is coupled to each wheelset in the vehicle model (moving track model). The applied track model describes the diverging route through the switch panel of the most common type of turnout applied in Dutch track: crossing angle 1 in 9, as described in [14]. The cross-sectional geometry through the complete switch panel has been built up from over 120 transverse rail profiles, measured in track at an average worn turnout, using the MiniProf Measurement system (Figure 4). The left and right rail profiles are measured individually. The switch toe is set as reference point (0.00). Profiles are measured in the plane of the track and so take into account the rail inclination. The profile measurement interval at the entry of the switch panel, the first meter behind the switch toe, has been set to 50 mm. Further into the switch panel the longitudinal profile discretization has been set to 200 mm and from meter 5 behind the switch toe to 400 mm. To simulate the changing rail profile through the turnout, VAMPIRE® performs an interpolation between tabularized wheel–rail contact data of each of the measured rail sections.

Switch geometry design values were further applied to the model (track gauge 1435 mm, no rail inclination). Apart from cross-sectional wear, no geometrical disturbances were included in the track model. The rail head profile is UIC 54 E1. The lateral rail to sleeper stiffness is set to a default value of 43 kN/mm, vertical rail stiffness per rail to 50 kN/mm. These values are assumed to be constant throughout the switch. The timestep in all simulations was 0.1 ms. No cut-off filtering was applied. Results plotting step size is 0.1 kHz

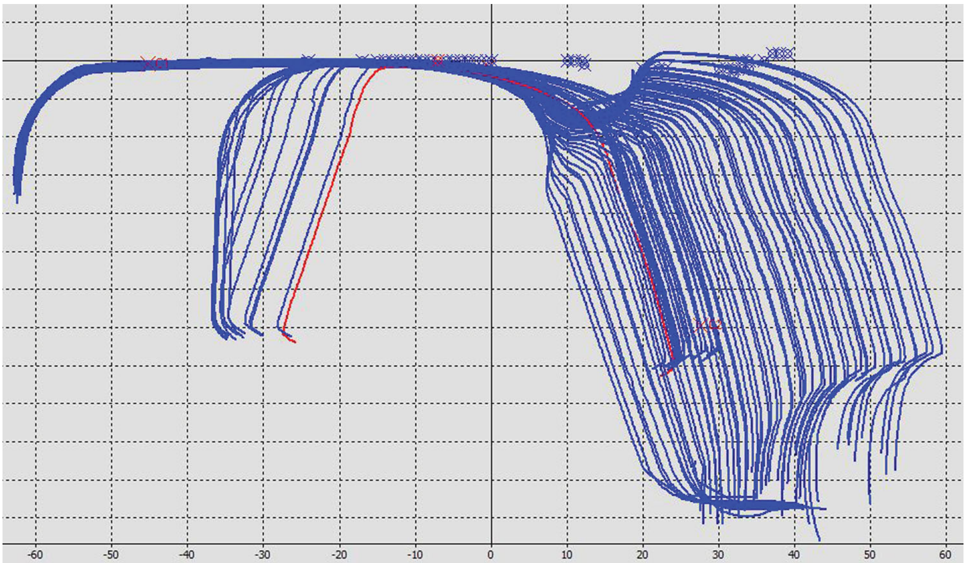

Figure 4. Overview of Miniprof rail cross sectional profiles measured at a section of the switch panel: the combined stock and switch rail serving the diverging route.

for all vehicle speeds. This corresponds to the frequencies proposed in [4] to capture the dynamic interaction for the changing rail profile at the turnout.

4. Wheel–rail damage criteria

Wear and Head Check damage development can be derived from the RCF damage function as presented in [15,16]. The main parameter in this function is the $T\gamma$ value (or wear energy number), which is a direct output from the VAMPIRE® multibody analysis. The parameter $T\gamma$ represents the dissipated energy between wheel and rail per travelled meter of track and is expressed in Joule per meter (J/m) or Newton (N). $T\gamma$ is the product of tangential force (T) and creepage (γ). The relation between the occurrence of visible RCF damage in R220 grade rail material is established in the RCF damage function as presented in Figure 5. In this graph, $T\gamma$ is plotted on the horizontal axis. On the vertical axis, the RCF damage

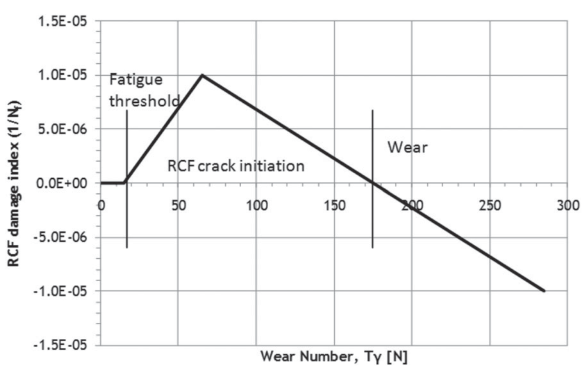

Figure 5. RCF-damage function for rail grade R220 [15,16].

index is plotted. The RCF damage index equals 1 divided by N_f: the number of loading cycles until the first visible Head Check damage occurs.

The RCF damage function has been extensively validated by comparing model predictions to Head Check propagation rate in track. It was found that there is a good correspondence between the model predictions and real-life observations [17]. A similar methodology for prediction of distributions of accumulated rail damage (wear and RCF) in railway turnouts has been presented and demonstrated in [18], involving simulation of dynamic train–track interaction and assessment of expected wear and RCF development.

Besides RCF, also the expected wear behaviour can be determined from the occurring $T\gamma$ value, since the wear load is closely related to this parameter. For the standard rail grade R220 an empirical threshold value has been established above, which wear behaviour transfers from 'mild' to 'severe'. This transition can be expected from $T\gamma > 200$ N, resulting in a significant increase in wear rate and surface roughness. Based on twin-disk testing, Lewis and Dwyer-Joyce [8] present the wear behaviour in relation to $T\gamma$ for the 'severe' wear regime. The wear rate is found to be a linear function of the wear energy number divided by contact patch area ($T\gamma$/A).

Assessment of $T\gamma$ loading distinguishes two contacting areas: the running surface (rail crown/ shoulder) and flange. Due to the high level of slip when in flange contact, wear loading in general here is significantly higher than at the rail crown or flange root contacting area.

5. Sensitivity analyses

A sensitivity analysis has been carried out by means of track-train simulations within the VAMPIRE® multi-body simulation software. Studying the contribution of identified parameters with respect to switch loading and related wear, $T\gamma$ values were assessed for the leading wheel. Since lateral wear is the result of wear loading at the flange, for this study $T\gamma$ development only is presented at flange contact. The parametric study was carried out involving train operational parameters that were identified as potentially dominating the resulting wear loading. The operational parameters considered are: vehicle speed, running direction, traction and wheel–rail friction level. Additionally, the influence of track gauge and track yard design was reviewed, in particular, the effect of multiple switches in short succession. Influence of the individual parameters is compared to a reference situation. The considered reference situation, for which only one parameter at a time was varied, consists of

- direction of traffic: diverging route, facing direction;
- connecting track to turnout: tangent;
- vehicle speed: 40 km/h;
- track gauge: 1435 mm;
- traction: active and
- no flange lubrication, wheel–rail friction coefficient set to $f = 0.32$.

To illustrate the overall dynamics at play for the modelled vehicle negotiating the 1:9 switch, the resulting lateral and vertical forces for the reference situation are presented in Figures 6 and 7. For the leading wheel of each bogie almost directly after entering the

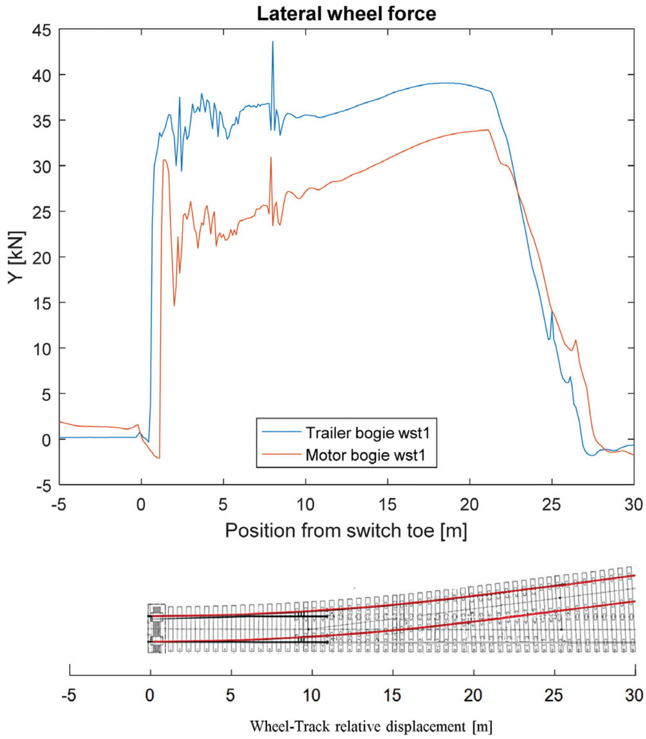

Figure 6. Lateral wheel force of at the leading wheel of the front bogie (trailer) and second bogie (motor).

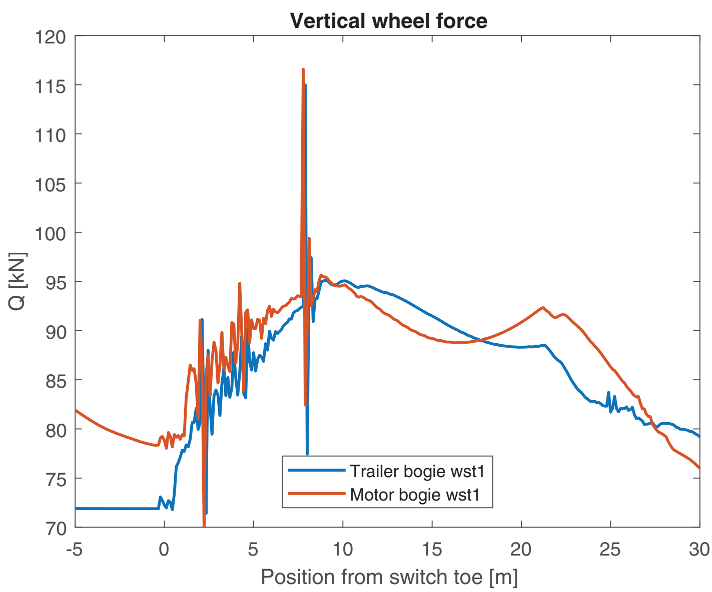

Figure 7. Vertical wheel force of at the leading wheel of the front bogie (trailer) and second bogie (motor).

switch flange contact occurs, resulting in a sharp increase in lateral wheel force. Throughout the switch panel and crossing panel the wheels remain in flange contact, showing a rather irregular behaviour during the first 8 m.

The irregular lateral and vertical wheel force values corresponding to the first 8 meters into the switch panel are caused by discontinuities in the wheel–rail contact conditions. The use of measured rail profiles at the switch panel, especially those combining stock and switch rail, will involve small alignment deviations between the successive measurement locations. These deviations and resulting changes of the wheelset relative to the rail cause the wheel–rail contact position to jump between switch rail and stock rail. This leads to abrupt changes in contact pressure, rolling radius and slip levels and is reflected in the observed sudden changes in Y and Q values, the overall development however remains clear. Beyond these first 8 m, the rail is described by a single measured profile, resulting in a steadier wheel–rail contact behaviour.

5.1. Results

Simulation results are presented and discussed for the assessed parameters.

5.1.1. Vehicle speed

Figure 8 presents the effect of train speed in relation to flange contact $T\gamma$ development at the leading wheel of the leading bogie. When negotiating the switch panel, three distinct peaks for $T\gamma$ are seen to arise. These occur from changes in contact position and corresponding changes in locations and orientations of contact forces and slip. Upon entering the switch, a first peak for $T\gamma$ arises due to the appearing flange contact. A second peak occurs when the wheel load fully transfer from stock rail to switch rail. A third peak arises

Figure 8. Wear loading for different train speeds. $T\gamma$ development at leading wheel of leading bogie.

at the end of the switch rail: at the transition of the machined switch rail profile to the nominal profile.

Figure 8 clearly shows the influence of train speed to be rather small. This observation is in accordance with the findings of the parametric study reported in [3] concluding that, for a give combination of wheel profile and axle load, the influence of train speed on contact pressure is small. Similar VAMPIRE® simulation results are reported in [19], presenting a modelled 1:9 turnout and container wagon (22.5 tons axle load). For the presented vehicle speed range of 5–50 km/h, it can be observed that the influence on wear energy development at the flange contact is very limited, this again in correspondence with the present study.

5.1.2. Wheel–rail coefficient of friction

The effect of the wheel–rail friction coefficient within the flange contact is presented in Figure 9.

The friction coefficient is seen to have a significant effect on the level of $T\gamma$ and the corresponding wear loading of switch and closure panel. Decreasing the friction coefficient from $f = 0.32$ to $f = 0.15$ will halve the lateral wear loading at the switch rail gauge face. For the lubricated (low friction) condition, the resulting $T\gamma$ values of 300 J/m for the leading trailer bogie and 200 J/m for the motor bogie indicate the switch rail to operate within the regime of full wear. The expected wear rate however is much lower compared to the non-lubricated (high friction) condition. From the resulting $T\gamma$ values in lubricated condition ($T\gamma \approx 200$ J/m), operation of the closure rails can be expected to be within the regime of mild wear for the leading bogie. For the motor bogie, with $T\gamma$ values for the reviewed configuration varying from 100 to 180 J/m, locally a shift into the RCF/wear regime is to be expected.

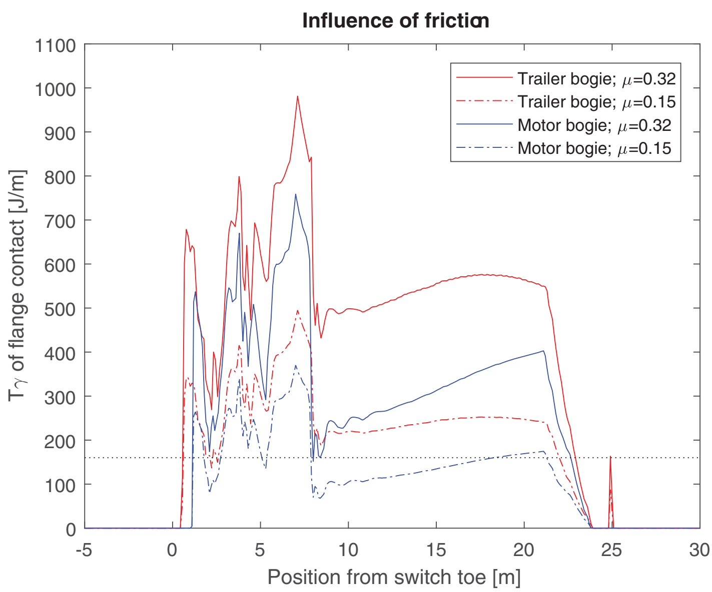

Figure 9. Wear loading in dependency on friction coefficient. $T\gamma$ development at the leading wheel of trailer and motor bogie.

Figure 10. Wear loading for different directions of traffic (trailing/facing). $T\gamma$ development at the leading wheel of motor and trailer bogie.

5.1.3. Direction of travel at diverging route

Figure 10 shows the effect of direction of travel at the diverging route, presenting the $T\gamma$ development for the leading wheels of first (trailer) and second bogie (motor). When travelling in the trailing direction (running along the point), the wear loading at the switch rail is seen to be 30% higher compared to the facing direction (running towards the point), as can be seen in Figure 10. The wear loading at the closure rail on the other hand is seen to decrease when travelling the diverging route in trailing direction. *Remark:* in both trailing and facing direction the applied vehicle orientation is equal with respect to the direction of traffic: the front coach is followed by intermediate coach.

This effect in wear loading can be explained by the relatively short curved section for this type of switch. When the leading bogie enters the curved section of the turnout, the second bogie will still be in the tangent track section. When going further down the curve the coach will start to rotate with respect to the second bogie, addressing the rotational resistance between these two. The resulting torque will increase the lateral (Y) force at the flange contact of the leading wheelset. When the leading wheelset has passed the switch curve, a similar however less pronounced effect will occur at the flange contact for the second bogie. This effect is illustrated in Figure 11, presenting the lateral (Y) forces when negotiating a curve with radius 195 m, curve length 20 m, without transition curves. It can be observed that for both the leading (trailer) bogie and second (motor) bogie the lateral forces at the leading wheel are gradually increasing.

5.1.4. Track layout, gauge and traction

The effect of the track layout has been considered by connecting the left-hand switch to a right hand curve with 195 m radius without cant, creating an S-shaped curve. The influence of this alignment set-up seems to be small. After negotiating the curve the lateral

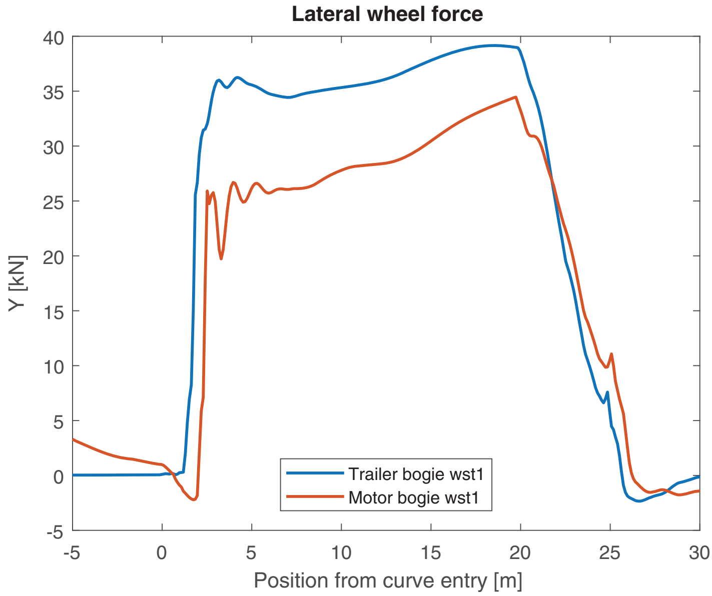

Figure 11. Development of the lateral (*Y*) forces when negotiating a curve with limited length (20 m).

position of the wheels is out of centre. This has an influence on the position where the wheel flange makes first contact with the switch rail, it however has no significant influence on the level of the wear loading. Increasing the gauge to 1445 mm does not show to have a significant influence on the level of wear loading, nor does traction show a notable effect.

6. Case study

An opportunity to expand the scope of this parametric study occurred when issues with severe switch rail wear were reported at a large number of 1:9 turnouts installed at the ProRail railway yard of Amsterdam Central Station (see Figure 12).

The most extreme case that was reported, was 1 mm of side wear within nine days, resulting in a significant increase in maintenance pressure and related cost for repair and renewal. A corresponding increase in side wear was also reported for the high rail of a number of narrow curves near the station. This abrupt increase in wear behaviour offered the opportunity to study the effect of possible changes in operational parameters to which modelling results can be cross-checked.

6.1. Problem analysis

In order to understand the setting and specific issues related to the observed dramatic change in lateral switch rail wear at the Amsterdam CS railway yard, it was decided to perform a systematic problem analysis. The involved parties were specialists of infrastructure manager ProRail, the responsible maintenance contractor and train-track specialists. The goal was to identify influencing factors and probable causes and deciding upon further

Figure 12. Severely worn switch rail (inspection December 2014).

analysis. The reported problem was first accurately defined, e.g. determining its characteristics and appearance, at what locations does the problem (not) occur, what is the normal value, what is the deviation and since when has the problem occurred. Also it is important to recognise if there have been changes to the system that could affect the (accumulated) wear loading of the switch panel, for example an increase in annual tonnage, change in operating trains and/or different routing of (freight) trains through the railway yard.

During the problem analysis a number of switches from the railway yard, equal in design, were reviewed. Based on maintenance and loading class, some in this group were ranked as 'severe' others as 'mild', corresponding to the experienced wear rate. From each of these groups switches were selected for further analysis. The reported dominating wear problem manifests itself at the switch panel, more specifically at the switch rail serving the diverging direction. Although for severely wearing switches also the closure rail suffers from excessive lateral wear, the small lateral wear limit value at the switch rail compared to the corresponding limit value for the closure rail determines the switch rail to dominate the resulting maintenance and renewal pressure. Reported switch rail life for the severely wearing switches has fallen to nearly three months. The trend in wear development of these switches is said to show a sharp deviation, which suddenly occurred at the end of 2013 – start 2014. To underpin these reported observations, historical data from these switches were analysed, consisting amongst others of individual switch loading development, accumulated tonnage for both passenger and freight trains, train-type operation and maintenance-related activities.

6.2. Operational data

For the selected switches, the accumulated yearly tonnage was analysed. Since 2010, following a re-routing at the track yard, both some of the 'mild' and 'severe' wearing switches have experienced a significant change in annual tonnage at the diverging route, together with a reversal of the dominant direction of traffic. This resulted in a 10-fold increase in tonnage in the facing direction and a corresponding decrease in the trailing direction (increasing

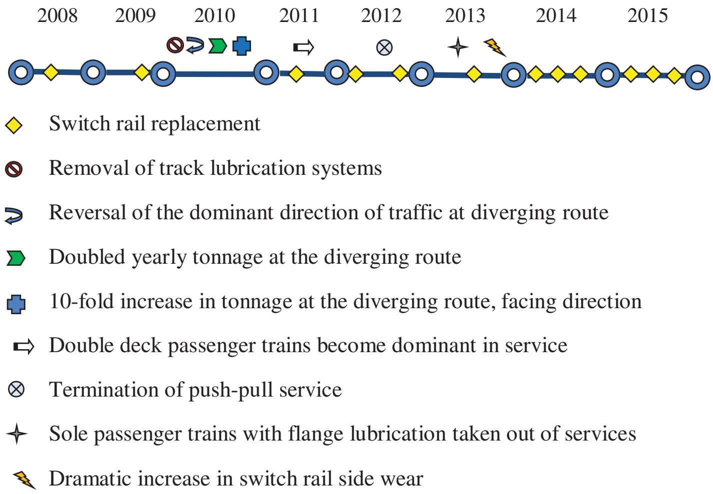

Figure 13. Switch rail replacement dates for one of the 'severe' wearing switches (left switch rail, serving the diverging route). Period August 2008 – September 2015.

from 1.2 to 12 MGT/year). Of the switches analysed, the lowest total yearly tonnage in the diverging route, with a very low contribution in the facing direction, belonged to a 'severe' wearing switch. Furthermore, contributions from passenger and freight traffic to the total tonnage in the diverging route was analysed. The contribution of freight traffic in the diverging route for one switch (mild wearing) is around 15% of the total tonnage (predominantly in facing direction). The contribution of freight traffic to the total tonnage for the other analyse switches is low, only 3%.

6.2.1. Switch rail lifetime development

The switch rail lifetime development of the selected switches was analysed from the contractor's maintenance logs. Figure 13 shows how the time interval between replacements has decreased for one of the 'severe' wearing switches, illustrating the effect of the increasing wear rate on rail lifetime. Around 2010 several changes occurred, as indicated in Figure 13. These changes are reflected by the replacement interval. During the period 2008 up to and including 2010 the average switch rail life is approx. 17 months. The involved maintenance specialists consider this life span as 'to be expected' given the extreme conditions at the Amsterdam CS yard. During the years 2011–2013, after the mentioned change in switch loading and routing in 2010, the average switch rail life is seen to decrease to approx. nine months. From 2014 the average switch rail life suddenly further decreases to approx. three months. For comparison: the in March 2011 installed left switch rail at one of the 'mild' wearing switches was to be replaced only in September 2015, after a life span of 53 months. Although over this period, the average annual tonnage in the diverging route for this switch is about 2/3 of that for switch illustrated in Figure 13, the observed difference in switch rail life is still significant.

6.2.2. Related switch maintenance issues

Switch panel maintenance firstly addresses safe passage of the wheels for the switch toe area. The main risk at this location is the development of a gap between switch toe and stock rail, causing the wheel flange to slip between stock and switch rail and, as a result, forcing the guiding wheel of the wheelset to travel the through route where the other wheel follows the diverging route. This will inevitably lead to a derailment. Regular S&C inspection involves service tests, wear and gauge measurements, checks of slide chairs, rail fastenings, lubricators (when applicable) and ultrasonic inspection. Routine S&C corrective activities involve, for example, manual rail profile maintenance (grinding), manual tamping, repair welding and component replacement. Also, the track alignment of the railway yard will influence the S&C loading and resulting maintenance demand. Due to the limited available space at the Amsterdam railway yard, successive switches are positioned in relatively close distance resulting in small radius connecting curves. This situation in alignment has not changed over the years.

Up and until 2010, track gauge-lubrication installations were present at Amsterdam CS. These installations were in operation at a number of switches and curves, aiming to reduce wear and flanging noise. However, in the experience of the responsible infrastructure manager and maintenance engineers, the cost of maintenance of these installations was considered to be high and effectiveness low due to frequent malfunction (e.g. inaccurate targeting resulting in the passing wheel flanges not to contact the lubricated area and/or absence of lubricant). At the Amsterdam CS railway yard, these track lubrication systems were removed in the year 2010, three years before the observed deviation from the trend in wear rate. When reviewing train operation at Amsterdam CS, it can be observed that the dominating train types over the years were passenger coaches type ICR and DDM in combination with NS locomotives 1700/1800 series (in push-pull service), together with passenger double deck trains of the VIRM type and freight trains (especially coal hoppers) with a range of freight locomotives. From 2010, VIRM-4 trains are gradually starting to dominate the passenger trains tonnage contribution at Amsterdam CS. From 2012, NS locomotives 1700/1800 are gradually removed from Dutch tracks, last visiting Amsterdam CS in the year 2013. Loco's 1700/1800 are the only type of NS trains fitted with flange lubrication. This implies that those switches and curves at Amsterdam CS that are only serving NS trains, passenger routes, do not receive any lubrication from passing wheel flanges. Freight locomotives are equipped with flange lubrication, hence rail at freight routes are (to some extend) expected to receive lubrication.

6.3. Track inspection results

Following the selection of 'severe' and 'mild' wearing turnouts, track inspections were carried out at the selected turnouts. Transverse profile, track gauge and roughness measurements were performed at several positions, together with visual inspections of the running band to assess the presence of RCF damage and lubrication. These results served as further input to the problem analysis. At the date of inspection (4 September 2015), the operational performance time of the inspected four left switch rails was, respectively, 1, 3, 6 and 52 months. During the track inspection, a distinct difference in visual appearance was observed between 'severely' and 'normal' wearing switches. Wear debris were clearly present at the switches with reported 'severe' wear, together with plastic deformation and spalling of the switch rail tip and high roughness of the gauge corner (Figure 14). The gauge corner of the switch with reported low wear rate, possesses a smooth running

Figure 14. Switch panel of 'severely' wearing switch (left switch and stock rail). Wear debris present, high roughness of gauge face. No lubrication marks.

Figure 15. Switch panel of 'mild' wearing switch (left switch and stock rail). No wear debris observed. At the gauge face remains of lubrication are present.

surface with no debris particles on site. At the switch rail gauge corner of this 'mild' wearing switch remains of flange lubrication were observed (Figure 15); the other inspected 'severe' wearing switches did not show any traces of flange lubrication.

7. Discussion

The simulations performed in this study have shown that switch rail lateral wear loading in the diverging direction of a 1:9 type turnout, is significantly influenced by the level of wheel–rail friction and to a lesser extent by the direction of travel. The other studied operational parameters, being vehicle speed, traction, gauge widening and track layout, showed no significant impact on the expected wear loading.

Those simulations in this study for which flange lubricated conditions were assumed, with a decreased friction coefficient, showed a local shift of the closure rail response into the RCF/wear regime when negotiated by the motor bogie. $T\gamma$ loading levels at the leading trailer bogie imply switch and closure rail loading to be predominantly within the regime of mild wear, with no expected RCF damage development. The significance of the wheel–rail friction coefficient regarding wear development was further underpinned by the case study results. The one distinct difference between the investigated ‘severe’ and ‘mild’ wearing switches being the presence of lubrication at the latter.

For the researched track configuration (turnout angle 1:9) and train operation, it is concluded that with respect to wear the dominant influencing factor is the wheel–rail friction coefficient. The identified most probable cause of the observed dramatic change in lateral wear development is a steep increase in the wheel–rail friction coefficient. After dismantling the track lubricators in 2011, no direct wear impact was observed, since the wear loading was kept to an acceptable level due to flange lubrication systems in operation at a number of the frequently visiting locomotives. However, from the moment that these vehicles with flange lubricators were no longer visiting Amsterdam CS (end 2013), the wear rate went up dramatically.

Following a sharp increase in wear loading at the flange contact, beside lateral wear of the rail, also an increase in wheel flange wear is to be expected. Inquiry at the NedTrain chief engineer, responsible for overhaul and maintenance of NS trains, confirmed this expectation. From mid-2014, a significant increase in wheel flange side wear is experienced, especially at intercity type trains VIRM and ICM. It is also confirmed that for these vehicles neither the wheel material quality nor the supplier have changed in recent years. This further underpins the conclusion that the experienced sharp increase in lateral wear is related to the interface properties and has a system wide impact: the absence of flange lubrication at passenger train dominated routes.

From the development in annual tonnage, it can be seen that the doubled tonnage at the diverging route in combination with a reversal in running direction did not result in a dramatic reduction in switch rail life. Not the annual tonnage seems the switch rail life defining parameter here, but much more the occurring wear regime. For the modelled setup, a change in wear regime from severe to mild could only be reached with decreased wheel–rail friction.

From the switch rail life development at Amsterdam CS, the effect of mode of operation (push-pull vs. pull) did not show to have a significant effect on the switch rail wear rate. With push-pull service ending in 2012 (changing to pull only), this change did not coincide with the witnessed sharp deviation in the wear development trend at the end of 2013 – start 2014.

Not included in this study is the effect of worn wheel or rail profiles, nor the effect of axle load. For the performed study, however, profile development seems not a governing factor, since the wheel profile variation of the dominating VIRM trains is very limited. The extremely short switch rail life seen at the case study, resulting in frequently installed new switch rails with new profiles, further indicates the effect of rail profile variations must be small. The limited impact of wheel and rail profile variation is further underpinned by the observation that can be made from the turnout with the main annual freight tonnage. Wheel profiles of freight wagons are known to vary more widely, nevertheless this turnout shows a significantly longer switch rail life. Since the axle load variation for the dominating VIRM passenger train is limited, also the effect of these variations will be limited for the studied configuration.

Following the dramatic wear development a field trial was initiated at Amsterdam CS, installing Head Hardened (HH) switch rails at a number of severe wearing turnouts. Although monitoring is still ongoing, first results confirm the expected HH-switch rail life to increase by a factor four compared to the standard rail grade when applied at these heavily loaded turnouts. For the HH-switch rail the observed wear regime is 'Severe' as well.

The considered modelling reference situation, for which parameters were varied, represents a severe load case which also is limited to only one (however dominant) type of train. In practice the $T\gamma$ loading will show a wider distribution, depending on the parameter combination for the individual event. Given a very unfavourable parameter combination, loading into the severe wear regime could still occur even in lubricated conditions. This implies that reduction of the wheel–rail friction coefficient at the flange contact will reduce the number of occasions at which the wear loading is raised into the severe wear regime. With proper lubrication applied to the configuration considered here, switch rail life is expected to return to levels before the dramatic change in 2013/2014.

8. Concluding remarks and future work

The wear loading at the rail surface resulting from trains negotiating railway turnouts in relation to train-track operational parameters is the subject of this study. A sensitivity study was carried out to understand the impact of possibly influencing train operational parameters regarding wear loading at the wheel–rail interface. This level of loading at the wheel–rail interface very much determines the required maintenance effort and costs. The operational parameters considered are vehicle speed, running direction, traction and level of wheel–rail friction. Additionally, the influences of track gauge and track yard design, in particular, the effect of multiple switches in short succession, were reviewed. Furthermore, a case study has been performed in response to a sharp increases in wear rate, reported at a specific location in the Dutch network. This case study supplied further insight into the system approach regarding wheel–rail management and allowed cross-checking the modelling output.

Based upon the executed problem analysis and turnout-train simulations, it can be concluded that the friction coefficient between wheel flange and rail gauge face is dominating the wear loading and related expected wear behaviour at the switch rail in diverging route. To a lesser extent also the direction of travel in the diverging route is of influence, with the loading level increasing with 30% for the trailing direction. Other studied operational parameters, being vehicle speed, traction and gauge widening showed no significant impact on the level of wear loading. Examining especially the effect of curves and switches in short sequence, track layout did not show to be of any significance to the resulting level of wear loading.

The most likely cause for the abrupt increase in switch rail lateral wear experienced at Amsterdam CS is the complete disappearance of flange lubrication when the sole NS trains equipped with flange lubricators were no longer serving this location. The presented study clearly demonstrates the contribution of flange lubrication in preventing abnormal wear at locations where the wheel–rail interface is severely loaded. Reported recent issues with an increasing wheel flange wear rate of connected trains seem to further underpin this conclusion. The application of flange lubrication, for the reviewed configuration, is expected to lower the wear loading at the wheel-rail interface to a level that operation in the 'Mild' wear regime can be expected for most of the switch and closure rail length in most operational conditions.

Together with a significant reduction in wear loading from flange lubrication, resulting in a shift from severe to mild wear, simulations performed in this study show the rail material respond at the switch and closure panel locally to shift into the RCF/wear regime. Rail grade selection in relation to $T\gamma$ loading levels therefore needs further work to prevent adverse side effects and to identify further optimisation opportunities.

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