Application of detailed theory at the rail / wheel interface – leading to smart solutions to maintain turnouts & predict derailment risk

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SUMMARY

Railway systems are facing high economic pressures for permanent optimization of operations to deliver transport services. In this economic era, choice of product is based on life cycle cost rather than standard procurement cost. The main drivers of the life cycle costs are operational & maintenance costs which exceed the procurement cost. From a supplier’s perspective these drivers can be influenced in a positive way by smart design parameters. Where in former times a lot of technical information of the product as well as maintenance limits have been specified by the rail infrastructure authorities, we can now see a global trend of railways focusing more on the overall outcome and performance of the system that is leading to the placement of more demands from suppliers to solve specific problems and also to provide detailed solutions for maintenance of the products. This development is also evident in Australia and is reinforced by the high personnel turnover as well retiring people with decades of knowledge and experience.

INTRODUCTION

Heavy haul industry in Australia operates with world’s heaviest axle loads and long hauling trains. In recent years a sharp surge in the productivity has tested the conventional rail products to its endurance limits. This has urged the high end manufacturers to adapt a holistic approach. Voestlapine VAE has developed a broad spectrum of high endurance rail products and has extended R&D service further into product life cycle analysis like,

- Wheel / Rail interactions
- Crossing running condition performance enhancement
- Gauge templates to aid maintenance activities

Some of the major network operators in Australia are embattling to increase the operational and maintenance efficiency and to eliminate catastrophic derailments. Mechanical failure in a track system can potentially cause derailments putting passengers life at risk and at the same time costings millions of dollars to recover from the incident.

As turnouts are highly susceptible to mechanical failure in the railway track system, many major railway operators in Europe and other continents have developed various switch rail monitoring systems to counteract such events. These practices closely address the wheel climb scenario caused by worn switch blades or worn wheels.
Some smart solutions to monitor, maintain & reduce turnout asset downtime are:

1) Development of tools for turnout maintenance on field to analyse safety against derailment on worn switch blades. All the prescribed tools enhance the turnout maintenance and renewal programs.

2) Optimisation of crossing nose geometry for a range of wheel profiles by developing detailed wheel transfer analysis models.

All these maintenance techniques developed based on European practices has several advantages compared to conventional maintenance which can suit Australian rail networks if used appropriately. Some of these concepts have been developed into hand held gauges that can be used in the field to enhance turnout monitoring and maintenance activities.

The focus of this paper is to diagnose the wearing pattern on switch blades which can trigger the wheel flange climb using interactive gauge templates. For example Figure 1, shows a worn gauge face of a switch blade which has past its condemning limit and requires a qualitative approach to validate the profile condition.

### NOTATIONS

- $L$ [N] Wheel vertical force
- $V$ [N] Flange lateral force
- $a$ [m / s²] Lateral acceleration
- $\delta$ [deg] Flange contact angle
- $\mu$ [-] Friction coefficient
- $F_2, F_3$ [N] Resultant force
- $F_z$ [N] Centrifugal force
- $F_g$ [N] Weight of vehicle wheel set
- $v$ [m/s] Speed
- $s$ [m] Track gauge + Head width
- $h$ [m] Vehicle center of gravity
- $g$ [g] Gravitational constant
- $R$ [m] Radius

### 1. Turnout safety analysis

Turnouts experience excessive wearing; especially the switch blades are susceptible to high lateral forces. Increasing the axle load elevate the stress on the rails and its supporting components. Hence it is vital to monitor the quality of switch blades by maintaining the profile shape and running conditions particularly in the wheel transfer area.

### 1.1 Single point contact

Single point contact in a wheel rail interaction is generally caused due by worn wheel with high conicity or due to plastic deformation in rail gauge face (as shown in Figure 2). This combination leads to highly concentrated contact stresses and results in undesirable running condition [2].

### 1.2 Conformal contact

The contact surface between the wheel thread, root & flange wear moderately together with rail gauge corner blending together to form a distributed load which acts as a desirable contact band (as shown in Figure 3). This contact band produces an optimal contact angle between the enabling to provide sustainable running condition [2]. It is becoming a common practice to
introduce superficial gauge corner wear to mimic existing wear which forms as a conformal contact.

**Figure 3: Conformal point contact (Distributed load)**

1.3 Flange climb limitation

Compared to tangent track, turnout switch sections are highly prone to flange climb. Particularly, in heavy haul systems with high axle loads, the switch blade wear is relatively high compared to other low axle networks. This is due to the extreme operational conditions, therefore require frequent monitoring services to maintain the reliability of the components. The high wear rate on the switch blades are caused due to abrupt change in the wheel trajectory increasing the angle of attack and introduces high lateral forces.

Factors influencing flange climb,

- Wheel flange angle & rail gauge face angle
- Angle of attack
- Co-efficient of friction
- Wheel rail profile condition

A train traversing through the turnout section in the absence of super elevation experiences tremendous force exerted by the vehicle (as shown in Figure 4).

**Forces exerted from the vehicle**

\[ F_Z = \frac{m \cdot v^2}{R} = L \]  
\[ F_g = m \cdot g \]

Sub (1) & (2) in eq. (3) implies

\[ V \cdot s = \left[ F_G \cdot \frac{s}{2} \right] + [F_Z \cdot h] \]

**Vehicle force exertion**

\[ \frac{L}{V} = \frac{2 \cdot s \cdot v^2}{\left(2 \cdot h \cdot v^2\right) + \left(R \cdot g \cdot s\right)} \]

It is desirable to maintain Wheel Lateral force (L) to Vertical force (V) ratio by refining the functions such as speed, turnout radius, loads. When contact between the wheel flange and the switch rail gauge face angle exceeds the permissible contact angle, it introduces flange instability in running condition.

**Figure 5: Flange contact angle (δ)**

\[ \frac{L}{V} = \frac{\tan \delta - \mu}{1 + \mu \tan \delta} \]

Based on Nadal’s limit criterion as shown in equation 5, High lateral force (L) or Low vertical wheel force (V) increases the likelihood of flange climb [2&9]. In the above L/V ratio equation, Friction coefficient (μ) plays a vital role where wheels with high friction coefficient complemented by low flange angles equates to
low L/V ratio limit potentially increasing risk of flange climb derailment [2, 8].

1.3.1 Flange contact angle

Contact angle (δ) between switch rail gauge face and the wheel flange in Nadal's criterion is one of the determining factor in the wheel climb. The profile relation between the two contact angles has to fall between the ranges of permissible contact angle deviation to maintain the equilibrium motion. Studies in various operational networks suggest maintaining high flange contact angle keeps the contact point sliding down relative to the rail [2, 8].

In this section we discuss about various empirical methods to ascertain the contact angle limitations. A wheel flange profile is replicated in a template format with permissible contact angle demarcations as shown in Figure 6. The templates are effectively positioned against the switch gauge contour in the transition zone along a pre-defined length to measure the contact angle and to ensure safe transition of wheels from switch rail to stock rail. Balancing or lowering the friction coefficient always minimises the risk of flange climb. Therefore, it is vital to monitor the contact angle in conjunction with well-balanced friction coefficient.

High degree of angle of attack in the switch transition introduces flange contact inducing high lateral forces thereby destabilising the equilibrium running condition.

Predominantly, all new turnout designs undergo static analysis depending on the all governing factors such as
- Speed
- Radius
- L/V limit

The L/V ratio criterion limits the risk of derailment and overloading on fastening components and operating systems. In order to achieve an equilibrium running condition it is essential to maintain the optimal contact angle effectively with an efficient grinding maintenance strategy utilising the contour templates.
1.3.2 Switch profile wear / damage

In modern turnouts, the switch blade has intricate design developed using asymmetrical, undercut and /or thick web profiles. The new switch profiles are enclosed within the stock rail and are less likely to be exposed to vulnerable flange attack compared to the conventional knife edge switch blades. Often due to heavy metal flow (Lipping) on the inner stock rail section, wide deflection occurs at the switch frontal section, exposing the blade to flange attack at the thinner section. Blade deflection due to negligible lifting techniques during installation is another factorial reason that can cause residual stress to form in irregular gaps. The gap/clearance beyond the rail transit standards identified in the switch blade will lead to immediate contact with the wheel flange and cause premature breakage.

Switch blade also tend to wear or break due to partially opened switch tip at the entry section. Figure 9 depicts the scenario of switch tip with potential opening clearance of “x” mm. The flange directly collides head on with the switch tip during the entry point, interrupting the smooth transition to the stock rail. In other instances, wheels with thin flanges have high tendency to split the switch tip from the housing at the entry, causing breakage and wheel uplift. It is therefore essential to maintain the switch tip profile to ensure the blade does not interact with the wheel flange. [2, 4, 9]

![Figure 9: Switch blade tip wear](image)

Precision templates as shown in Figure 10, can be manually utilised during maintenance activities to measure the allowable clearance set by the network standards between the switch and the stock rail. Further rectifications can be carried out if any excessive gap is identified either by adjusting the switch machine to achieve the clearance or by replacing the switch blade.

![Figure 10: Probe to measure switch gaps](image)

1.3.3 Switch blade gauge face wear

Turnout experience “angle of attack” or “Yaw angle” in the switch curve as mentioned in the previous section is due to acute angle alignment between wheel and rail. This introduces constant flange contact creating a two point interaction for a certain distance inducing high lateral forces (L) to be exerted by the wheel flange that will rupture the thin sections of the blade (Figure 11). The gauge face wear is also influenced by other external factors like foreign body intrusion and thermal stress that can potentially lead to wear or breakout

![Figure 11: Switch blade gauge face wear](image)

Due to the fragile section of the switch blade, vertical & horizontal wear including break outs have to be vigilantly monitored along the wheel transition area. As a part of visual inspection, gauge templates with the permissable wear limits [2&9] (based on the flange climb theorem as depicted in Figure 12), can be utilised as a guideline to monitor the defects and impose appropriate speed restrictions based on the severity of the condition.
1.3.4 Stock rail head wear & gauge face wear

Relative change in the vertical height difference between the switch blade and the stock rail alters the wheel transition zone in the switch section. The transition zone in the switch section is affected by

a) Switch/Stock rail height difference

b) Wheel profile condition

Vertical head wear of the stock rail as depicted in the Figure 12 exposes the switch blade to wheel sets at an earlier stage leading to earlier transition in the weaker sections of the switch blade. This causes irregularity in wheel transition and poses a potential threat to flange run over the machined area of the switch blade.

Figure 12: Schematic condition of stock rail head loss

To mitigate the risk of early transition and flange running on the switch, the head loss of the stock rail has to be effectively controlled by adapting well-structured grinding strategy. Onsite visual inspections can be well accompanied with customised gauge templates as depicted in Figure 13 to monitor the head loss within permissible limits. Once the stock rail / switch rail reaches its life span, it is ideal to replace both the switch and stock rail. When replacing or refurbishing stock rails or switch blades, it is recommended to consider the pair rather than an individual component, to avoid early degradation of the new component and inconsistencies in wheel transition.

Figure 13: Gauge template for measuring stock rail head loss relative to switch blade height

The main purpose of adopting such control measures is to reduce the likelihood of flange climb in the switch transition area and to provide an indicative guideline for worn-out componentry during maintenance activity. Incorporating profile measurement using gauge templates and a monitoring program will evidently improve the effectiveness of operational activities.

The existing formulations proposed by Nadal’s L/V limit criterion [1, 2, & 9] are analysed during the feasibility phase to ensure the safety and stability of the turnout.

All new switch and crossing designs are evaluated with new/worn wheel geometry to optimize the profile characteristics [6]

2. Geometrical analysis

Conventional crossings are relatively designed to function under limited operational conditions. In recent years increase in operational needs and advances in wheel profiles has significantly reduced the performance of the crossings as the wheel/rail interaction becomes more critical. A comparative study of the geometrical analysis between the old and new wheel transition will characterise the impact conditions and provide opportunities for improvements in the running conditions.

2.1 Nose ramping

Crossing is a part of a turnout that functions to deter the train at the crossing angles. It has similar function to switches that is used to transit the wheels sets to the required segment. A fixed
crossing in particular has a discontinuity in the line causing an abrupt change in running condition. This discontinuity amplifies the magnitude of high frequency dynamic forces (P1) acting on the nose. The forces introduced by the wheel sets lead to earlier degradation of the crossing. The geometry of the wing rail and point rail contour defines the transition of the wheel sets in the fixed crossing. The constant dynamic impact between the nose and the wheel set induces contact stresses, forces and pressure. The changes in the surface condition of the crossing due to the forces results in Rail contact fatigue (RCF)

- Wing rail
- Wing rail nose (Transfer area)
- Point rail consecutive head widths

2.3 Nose load distribution

The nose ramping of the fixed crossing is evaluated at defined cross sectional intervals to examine the static contact band. The contact band generally is of two types:

- Single point contact
- Distributed contact

The ramping profile is modified to achieve a modest level of conformal contact band between the wheel and crossing nose. This combination matures in the long run due to controlled wear by wheel / rail interaction which can be further complimented by regular general maintenance.

2.2 2D Wheel impact considerations

The investigation entails study of static contact geometry focusing on initial load section (transition area) and the course of wheel vertical displacement over the nose section. The wheel transition from wing rail to point rail is clearly identified with the 2D new and average worn wheel profile passing through different stages

- Impacts
- Wear
- Metal flow
- Surface and sub-surface defects

Figure 14: Fixed crossing nose (compound)
2.4 Lateral wheel position at nose entry angle

The Entry nose impact design is progressively studied to control the lateral displacement of traversing wheel sets through the transition zone. Traversing position of the wheel sets is effectively controlled by adjusting the check rails to reduce lateral imbalance in the unguided area to achieve minimal impact to the nose. The wheel sets positions are controlled to avoid any earlier nose transfer that would result in over loading in the narrow sections of the crossing nose. This controlled displacement is investigated within the limitations of transit standards. [10 & 12]

2.5 Nose ramping optimisation

Studies carried out on crossing geometry between the conventional and modified nose ramping based on parameters collected on the field, has clearly distinguished the nose impact zones from wheel impacts. The optimised nose profile experiences wheel transition at a wider section with a gradual wheel ramping as compared to conventional nose ramping with abrupt change in the wheel displacement causing unpredictable impacts.

The graph in Figure 20 illustrates theoretical analysis of nose ramping comparison performed on new and existing crossing designs based on the current operating conditions in the network. The results achieved from the comparative study can be verified through empirical measurements on site using various commercial profile measuring devices to ascertain the results. This optimisation process has a significant impact on the crossing life cycle increasing the rate of return.
2.6 Gauge templates to measure nose ramping

It is practically challenging to achieve the actual profile shape of the crossing nose and ramping once the product is in service. The nose profile diminishes or deteriorates in the long run either due to flow of traffic, various grinding practices or damages caused due to external factors. Often the breakages on the nose require welding to re-build the profile. Maintaining the crossing profile to the right geometry is quite crucial to maintain the tranquillity of the crossing and prolong the life cycle of the product.

Hence it is recommended to closely monitor and measure the nose geometry using template as shown in Figure 21 to aid preventative & corrective maintenance activities.

Gauge templates with different nose cross sections as shown in Figure 24 can effectively assist in grinding to shape the nose profile and to rectify/balance the differential height between the wing rail and the nose to maintain a smooth transition. It also acts as a guiding template to achieve consistency, particularly, when re-welding the nose surface or the wing rail to reinstate the geometry.

To attain the predicted product life cycle, adequate maintenance is required in defined intervals. The frequency of maintenance periods can be established based on operational performance and degradation rate. The focus of the profile optimization and gauge templates is to enhance the quality of the maintenance work and prolong the lifecycle of the system before it reaches its condemning limit.
3. Conclusion

Turnout technology in the last few years has grown exponentially with reliability being the key factor contributing to its sustainability in complex operational conditions. It is highly essential to understand the working principle of turnouts and find the right balance between performance and reliability.

Whilst developing asset maintenance strategy for turnouts, it is vital to localise turnout in sections such as switches, crossings and closely monitor the critical section based on new and worn wheel profiles. Choosing the appropriate design, components and maintenance model to suit the operation is essential.

To maintain the quality of the turnouts, it is essential to embrace qualitative maintenance activities accompanied by adequate data collection and analysis. To complement this process appropriate tools and techniques can be integrated in the system.
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