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Design and performance analysis of a Tram-Train profile for dual operation running

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ABSTRACT

This paper explores the design of a new wheel profile for use on a Tram-Train vehicle. A Tram-Train is a dual-mode vehicle that operates on two very different railway infrastructures; as a tram on light rail infrastructure and as a conventional train on heavy rail infrastructure.

The wheel/rail interface challenges have been highlighted and discussed and the analysis and design process required to develop an optimised wheel profile for dual operation running has been presented.

One of the key issues in developing a dual-operation wheel profile was managing the contact conditions within the wheel/rail interface. The interface is critical not only to the safe running of the vehicle but also to maximise asset life and to minimise wheel-rail damage. A combination of vehicle dynamic simulations and bespoke software were used to allow the development of a new wheel profile for Tram-Train operations.

Keywords

Tram-Train, Wheel/Rail Interaction, Wheel/Rail Profiles,
Train Dynamics, Simulation, RCF, Wear

INTRODUCTION

A Tram-Train is a dual-mode vehicle that operates as a tram on light rail infrastructure and as a conventional train on heavy rail infrastructure. The first Tram-Train scheme was in Karlsruhe, Germany, in the early 1990s, the concept has now spread successfully to several other European cities.

To demonstrate that the benefits of Tram-Train can be realised in the UK, a pilot project was set up by the Department for Transport (DfT) with Network Rail, Northern Rail, Stagecoach Supertram and South Yorkshire Passenger Transport Executive (SYPTEx) as partners. The selected route for the scheme is approximately 12.2km long; consisting of 6.5km on the Sheffield Supertram (SST) light-rail system, running from the centre of Sheffield, before connecting with Network Rail (NR) heavy-rail infrastructure via a purpose built chord at Tinsley near Meadowhall Shopping Centre, from where it completes the remaining 5.7km of the route to Rotherham.

There are many system interface issues that the Tram-Train vehicle design was required to address to enable running on both light and heavy rail infrastructures, including amongst others; signalling, platform heights, overhead line equipment and wheel/rail interaction.

This paper discusses the wheel/rail interface challenges and the design of a bespoke wheel profile to allow safe running on both SST and NR infrastructure. The specification and design process followed during the evolution of the wheel profile are presented and the rationale behind the design choices are given. The paper also describes the required design assurance which has been carried out to ensure the new profile has sufficient resistance to derailment, is compatible with switches and crossings (S&C) and has acceptable

performance in terms of wheel-rail rolling contact fatigue and wear.

Interface Challenges

Wheel profiles are normally designed or selected to be compatible with the rail profiles and track construction used on a particular system. As a result of this, the existing wheel profiles used on SST and NR are very different when compared to one another; Figure 1 shows the two profiles and key dimensions. The SST vehicles use a wheel profile [1] that is typical of tramway applications; low conicity tread compatible with the flat crown (rail head) of rail profiles such as 55G2 [2] and 39E1 (BS80A) [3] used on the SST system, a steep 76° flange for high derailment resistance on tight curves and a flat flange tip for flange tip running through switches and crossings (S&C). On NR infrastructure there are a range of approved profiles which are defined in the Railway Wheelsets Group Standard, GM/RT2466 [4]. The most common profile on the NR section of the Tram-Train route is the British Rail (BR) P8 profile which is commonly used throughout the UK and is compatible with all NR infrastructure. The P8 profile has a shallower flange angle of 68° and its tread is a 'pre-worn' shape suited to the smaller crown radii of NR rail sections.

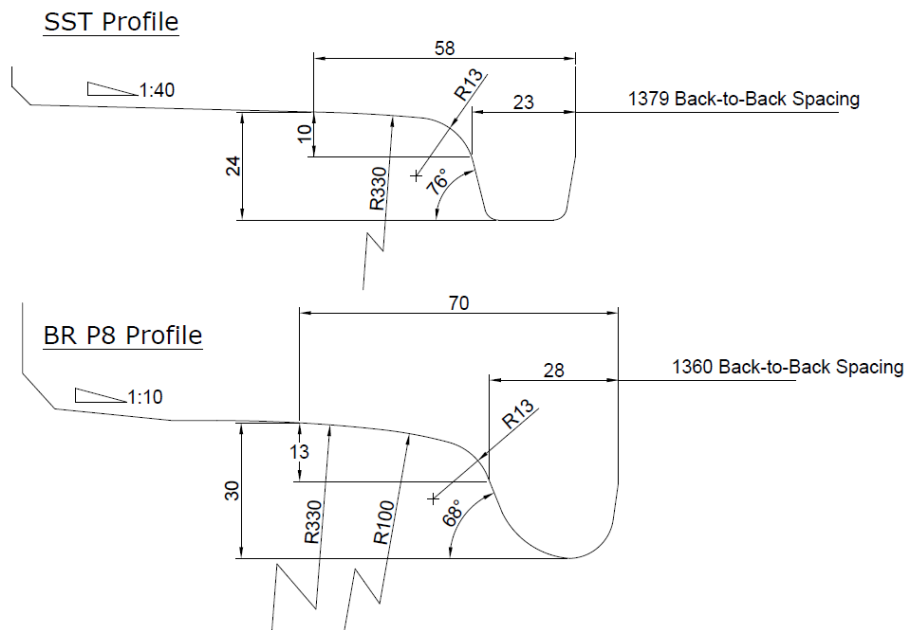


Figure 1: Existing SST and NR wheel profiles

Initially the SST tram wheel profile and the British Rail P8 (BR P8) wheel profiles were considered for use on the Tram-Train vehicle, however, the following wheel/rail interface challenges were identified:

- Geometric compatibility with grooved rail on SST street sections
- Different wheelset back-to-back spacings for SST and NR wheelsets
- Different rail head profiles
- Different S&C designs
- Flange Tip Running on SST

Grooved Rail

On street sections of the SST system the track is formed using a grooved rail section. Tram profiles have a narrower flange than heavy rail profiles to allow the groove width to be minimised whilst still providing the necessary clearances to allow the wheelset to negotiate curves

effectively. NR wheel profiles, such as the BR P8, are not suitable for use on SST infrastructure as the wider flange leaves insufficient flangeback clearance to the keeper rail to allow the wheelset to steer effectively in curves. Figure 2 shows an SST and a BR P8 wheel profile on a grooved rail section.

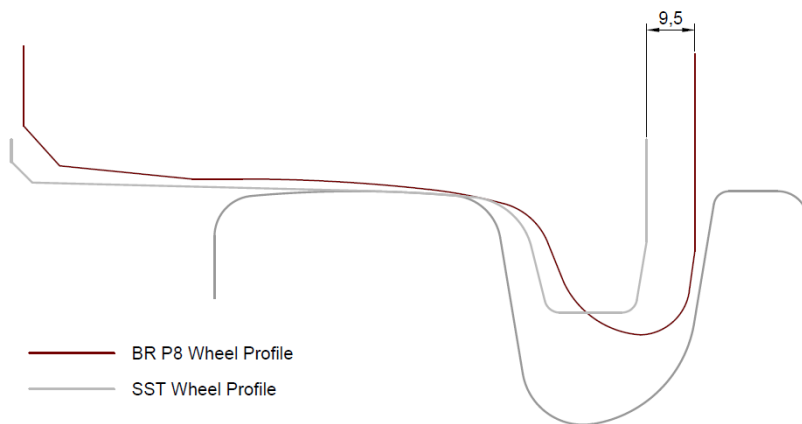


Figure 2: Wheel Profiles on Grooved Rail

Back-to-Back Spacing

When negotiating Switches and Crossings (S&C) the wheelset is guided through the acute crossing nose by a check rail contacting on the opposite wheel's flangeback. The check rail prevents the flange tip from striking the crossing nose or the wheel taking the wrong route all together. The back-to-back spacing of the wheelset is therefore a critical dimension. Although SST and NR use the same nominal track gauge of 1435mm, the SST wheelsets have a wider back-to-back spacing when compared to standard NR wheelsets to compensate for the narrower flange. Figure 3 shows the critical dimensions of a BR P8 and SST wheelset.

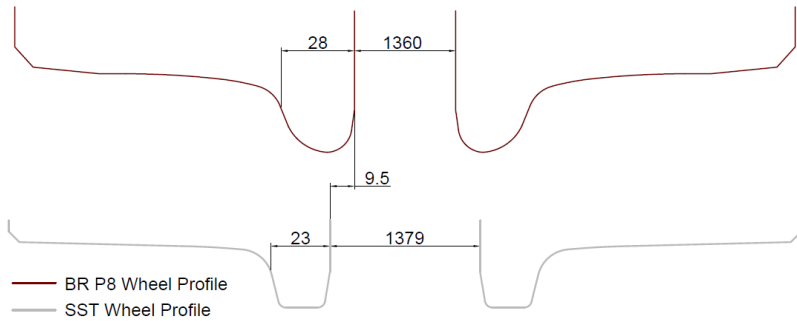


Figure 3: Wheelset Dimensions

The wider flangeback spacing of the SST wheelsets precludes the use of the SST tram profile on NR infrastructure where the S&C are designed for a back-to-back spacing of 1360mm. Figure 4 shows the interaction of a BR P8 and an SST wheelset on an NR acute crossing; It can be seen that the BR P8 profile is held off the crossing nose by the check rail whereas the SST profile will strike the crossing nose. In addition to this issue the SST wheelset will not engage with the check rails on tight radius checked curves which could pose an increased derailment risk.

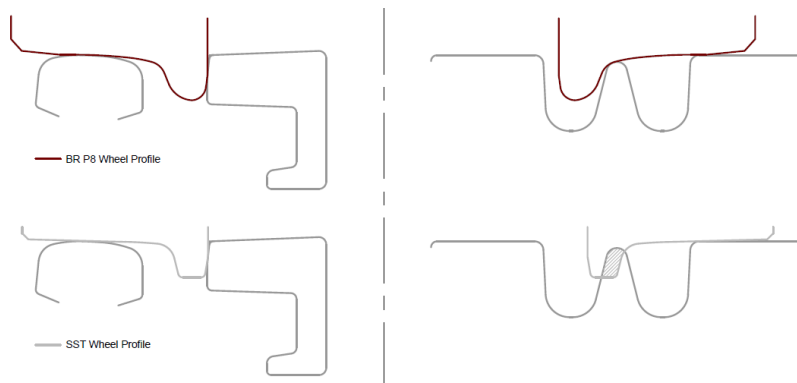


Figure 4: Acute crossing nose interaction of BR P8 and SST wheelsets

Different Rail Profiles

The Tram-Train route has a combination of new and worn rail profiles of both grooved and vignole (flat bottom)

type. Table 1 lists the installed rail profiles on the Tram-Train route.

Table 1: Rail Profiles used on Tram-Train route

Profile	Standard	System	Rail Type	Inclination	Track Type
39E1 (BS80A)	EN 13674-4 [3]	SST	Vignole	0 (Vertical)	S&C
				1:40	Ballasted Track
55G2	EN 14811 [2]	SST	Grooved	0 (Vertical)	Embedded Track
54E1	EN 13674-1 [5]	SST	Vignole	0 (Vertical)	Viaduct
BR113A (56E1)	EN 13674-1 [5]	SST	Vignole	0 (Vertical)	Ballasted Track
		NR	Vignole	1:20	Ballasted Track
SST Worn	-	SST	-	-	-
NR Worn	-	NR	-	-	-

Wheel profiles are normally selected or designed to be compatible with the rail profiles on a given system by optimising the wheel/rail contact conditions; this includes minimising contact stresses and providing appropriate levels of conicity and rolling radius difference to facilitate good curving performance and to minimise wear. To adopt a wheel profile compatible with only one system may generate unfavourable contact conditions on the other, resulting in derailment risk, increased wear and rolling contact fatigue, plastic flow and dynamic instability of the vehicle.

In addition to the new rail profiles on a system, there are also the existing worn rail profiles to consider. In relation

to wheel/rail contact conditions it was found that measured worn rail profiles of 39E1 and 55G2 from SST had the same shape and therefore only one worn rail profile for SST needed to be considered [6]. It was also found that NR rails tended to wear to the same shape, that of a P8 wheel, so similarly only one worn NR rail profile was considered. The high rails on curves of different radii tend to wear to the same shape over time but at different rates, it was therefore possible to consider one worn profile shape as a worst case for all curve radii. On tangent track and low rails in curves the wheel tread will be in contact with the rail head resulting in low contact stresses; The lower stresses mean that wear rates tend to be much less than for the high rail so this case has been neglected.

Typically as a rail wears it tends to adopt the shape of the wheels running on it, such that the NR worn rail shape is similar to a BR P8 wheel and the SST worn rail profile is similar to the SST wheel profile. This conformity is demonstrated in Figure 5.

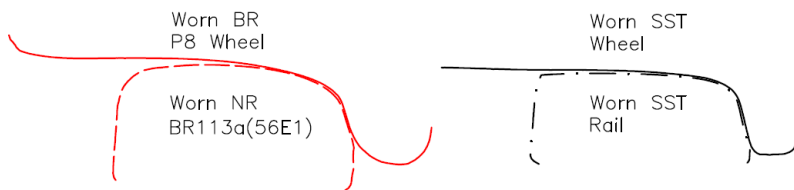


Figure 5: Conformality of wheel and worn rail profiles

Figure 6 shows the most prevalent new rail profiles and the corresponding worn profiles found on the Tram-Train route. The new 39E1 and 55G2 profiles which are installed on SST have virtually the same gauge corner and head profile giving similar contact conditions, the main difference is the keeper rail on the 55G2.

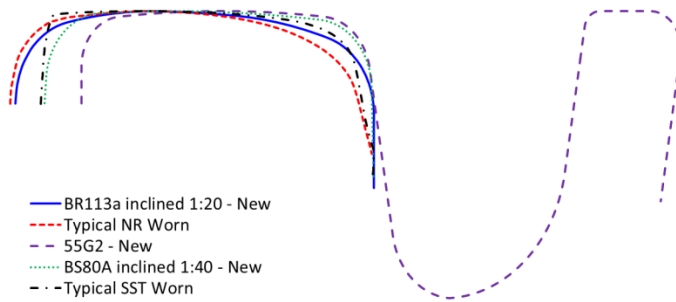


Figure 6: Prevalent rail profiles on Tram-Train route

When comparing the new and worn SST and NR profiles it can be seen that there is a large variation in shapes, the key differences being with the gauge corner and crown radii. Table 2 provides some key dimensions of the new and worn vignole rail profiles on the Tram-Train route. The worn profiles have a small amount of head and side wear with the majority of the wear being around the gauge corner.

Table 2: Key dimensions of new and worn rail profiles used on Tram-Train route

System	Profile	Head Wear (mm)	Side Wear (mm)	Gauge Corner Radius (mm)	Intermediate Radius (mm)	Crown Radius (mm)
SST	39E1 (BS80A)	0	0	11.1	-	305
	SST Worn	3.6	1.8	8.44	24-150	400
NR	BR113A (56E1)	0	0	12.7	80	305
	NR Worn	0.7	2	15	50	150

Switch Blade Interaction

Switch blades are designed to be compatible with the wheel profiles running on them to ensure safe passage of the wheelsets. It was identified that the SST tram wheel profile was not compatible with NR standard switches as there is a

possibility of the flange striking the switch tip which could lead to a derailment. Figure 7 illustrates how a BR P8 profile clears the switch tip whereas the SST tram profile creates a clash. The scenario in the figure shows a cross-section of the tip of the switch blade when positioned at its maintenance limit of 3mm residual switch opening.

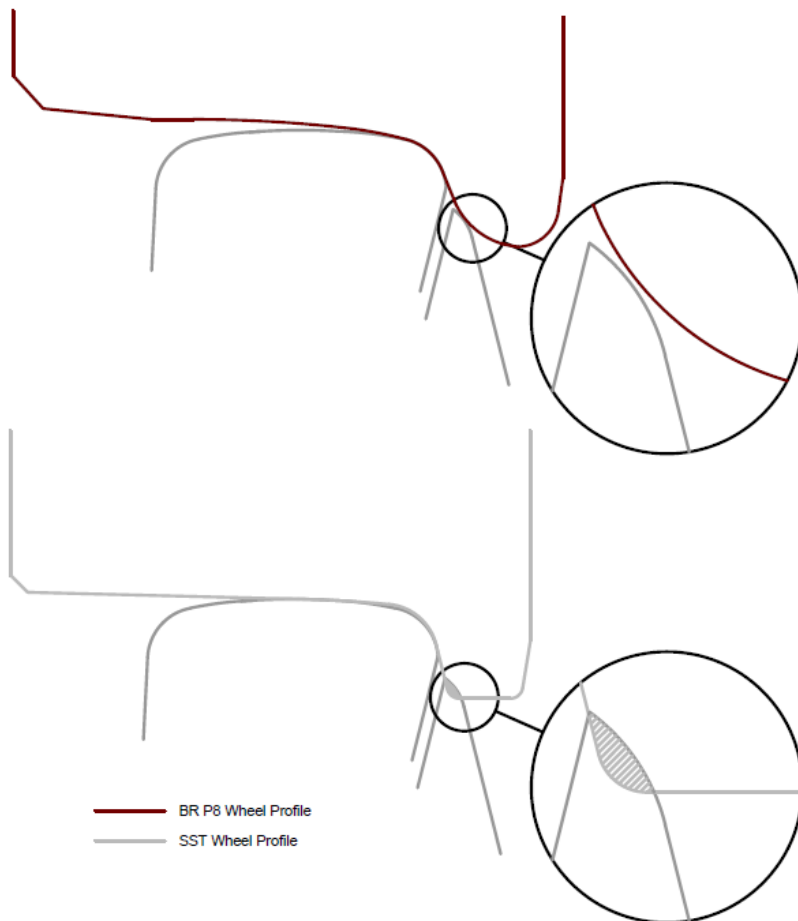


Figure 7: Wheel profiles on NR Switch with residual switch opening

Flange Tip Running

In some locations on SST flange tip running is employed on S&C diamond crossings. This is where the flange tip is used to carry the vertical wheel load whilst the tread passes over the crossing, the primary benefits being improved ride quality and reduced impact forces at the crossing. To facilitate flange tip running the SST wheel flange has a flat tip to distribute the vertical load thus reducing contact stresses. On NR infrastructure there is no requirement for flange tip running and hence the BR P8 has a conventional flange shape. If the BR P8 profile was used for flange tip running then contact stresses would be higher which could lead to plastic deformation of the flange tip and potential associated wheel-rail interface problems.

PROFILE DEVELOPMENT

In order to run a Tram-Train vehicle on both tramway and heavy rail infrastructure the interface challenges outlined in the previous section needed to be addressed, this required the development of a new wheel profile for dual mode operation.

An initial study considered a range of existing wheel profiles for use on Tram-Train [6]. The study concluded that none of the current UK tramway wheel profiles, including the current SST wheel, were suitable for use on NR infrastructure due to severe two-point contact at relatively large curve radii, resulting in accelerated wheel and rail wear. However the study did find that a BR P8 wheel profile geometry generated similar wheel-rail wear rates on SST infrastructure as the current tramway profile and therefore could potentially form the basis of a possible Tram-Train profile design. This is demonstrated in Figure 8 and Figure 9 which shows the $T\gamma$ (contact patch energy – the product of creepage and creep force) generated on the high rail tread and flange for a range of curve radii. Higher $T\gamma$ values equate to higher wear rates as shown by work carried out by British Rail Research (BRR) [7]. The plots in Figure 8 for NR infrastructure show that the predicted $T\gamma$ is slightly higher on the tread for the SST wheel

when compared to the NR P8 and considerably higher on the flange. Plots on SST infrastructure show that the P8 and SST profiles perform in a very similar manner for both new and worn rail profiles.

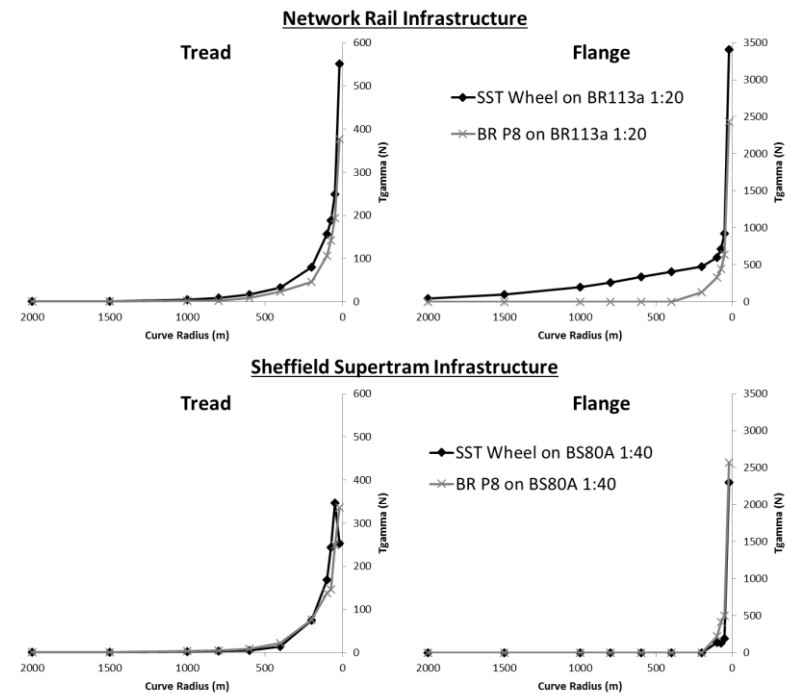


Figure 8: $T\gamma$ vs Curve Radius for SST and NR P8 wheel profiles on NR and SST infrastructure with new rail profiles

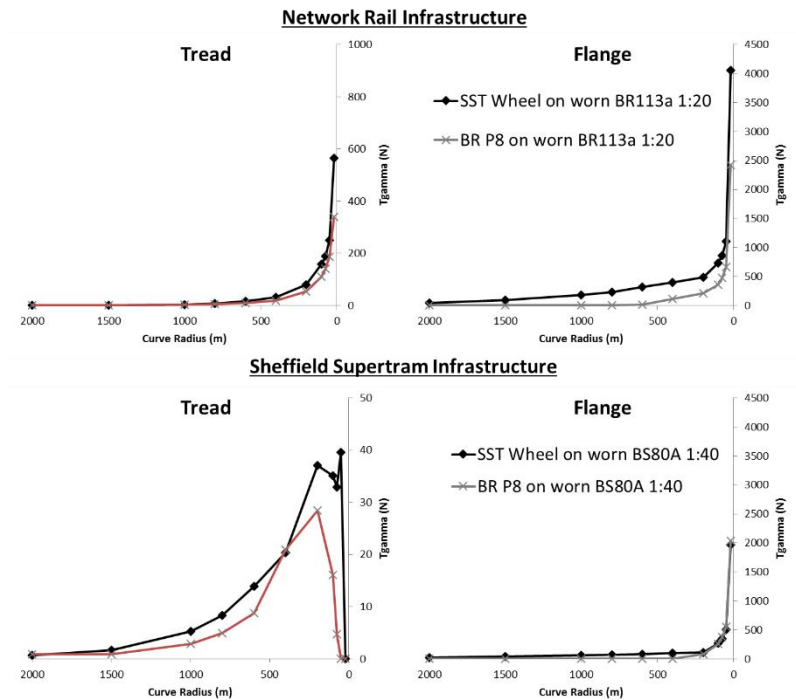


Figure 9: $T\gamma$ vs Curve Radius for SST and NR P8 wheel profiles on NR and SST infrastructure with worn rail profiles

Based on the initial study, it was decided that a hybrid profile should be developed with tread geometry based on the BR P8 profile in conjunction with other features to ensure interoperability on the two systems. The new profile required the following features:

- P8 type geometry from flange face across the extent of the tread to provide compatibility with both NR and SST rail profiles.
- 68° flange angle for compatibility with NR switch toes and facilitate the required 3mm of residual switch opening (RSO).
- SST flat flange tip for flange tip running through diamond crossings on SST.
- SST flangeback angle to create similar keeper/check rail contact conditions on the tramway.

- Cut-out in back of wheel to provide two checking faces – one for NR and one for SST.

Figure 10 shows the Tram-Train profile which combines all of the required features listed above.

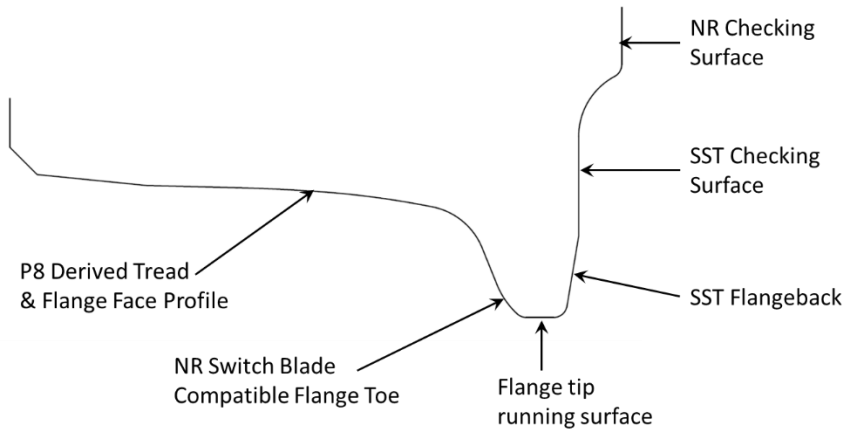


Figure 10: Tram-Train profile before the design iterations

Beginning with the first design iteration of the Tram-Train profile, a series of other profiles with stepwise refinements were made. The methodology used for profile development was:

1. Determine new and worn rail section crown and gauge corner radii using relevant standards and 2D CAD.
2. Modify profiles to improve conformality between wheel and rail profiles to avoid distinctly separated two-point contact which can lead to high wear rates.
3. Develop flange and flangeback geometry to ensure correct geometric fit e.g. checking faces are in the correct locations.
4. Assess contact conditions for suitability:
 - a. Rolling Radius Difference
 - b. Equivalent Conicity
 - c. Contact Angle
 - d. Contact Patch Area

5. Dynamic simulations to assess curving performance in terms of $T\gamma$ and Contact Stress.
6. Review design and repeat as necessary.

A total of 7 different profiles were developed and assessed. The profile design which met all of the geometric requirements and provided the best overall performance on SST and NR infrastructure was selected as the final design. It is this final iteration which forms the basis of the analysis within this paper.

Contact Conditions

For each developed wheel profile a set of contact data was generated using each of the rail profiles found on the Tram-Train route. The contact data was created using the Contact Data Generation program within the VAMPIRE[®] vehicle dynamics simulation software [8]. The data contains information describing the geometric contact conditions between wheel and rail for a series of lateral positions of the wheelset relative to the rail. Contact data was calculated using the nominal wheel diameter, nominal gauge and the laden axleload for the Tram-Train vehicle. The parameters of interest were rolling radius difference, contact angle and contact patch area. The Contact Data Generation program also calculates the equivalent conicity of the wheel rail combination.

Each parameter was compared to the base cases of the existing SST new and worn wheel profile on SST infrastructure and a new and worn BR P8 wheel profiles on NR infrastructure. The following subsections explain the different contact data parameters and the results of analysis for the proposed new Tram-Train wheel profile.

Rolling radius difference

Rolling radius difference (RRD) is the difference between the wheel radii at the contact patches of the left and

right wheels. The RRD is the mechanism through which a conventional wheelset self-steers on curves. The plotted RRD curve provides an indication of the level of steering that a wheel profile will generate as well as helping to identify if, or at what lateral shift, two-point contact occurs. It is desirable to develop a conformal wheel profile that avoids severe two-point contact as this helps to prevent excessive $T\gamma$ levels and high wheel-rail wear rates [9]. Two point contact with a large difference in RRD between the two contacts results in an imbalance of the longitudinal creep forces giving rise to higher creepages and therefore wear. Developing a conformal profile also delivers the benefit of distributing the contact patch, and therefore wear, across the whole wheel and rail rather than generating distinct bands of wear.

The desired RRD plot should therefore have a smooth transition from tread to flange contact without significant jumps (in the order of 10mm) which would indicate two-point contact. In addition, the gradient of the RRD plot indicates the conicity of the wheel/rail profile combination, with the conicity being half of the gradient for a linear profile. The conicity of the profile is important as a high conicity will provide good curving performance but will make the vehicle more susceptible to a lateral instability mode, also known as hunting. Although good curving performance is desirable, poor lateral stability should be avoided as it is detrimental to passenger ride comfort and wheel-rail asset life. A low conicity profile combination would have a conicity of around 0.05 whereas a high conicity profile combination could be 0.5 or higher.

Figure 11 shows the RRD plots for new and worn SST wheel profiles and the new Tram-Train wheel profile on worn SST rail. The new and worn SST wheel profiles provide little RRD up to the point of flange contact, at which point the RRD rises rapidly. The jump in the RRD for the worn SST profile between 6 and 7mm lateral shift is due to the manner in which the side worn rail profile interacts with the wheel flange resulting in the contact patch jumping up and then back down

the flange. The Tram-Train wheel profile provides a higher level of RRD on the tread, indicating higher conicity and therefore better curving performance. The transition into flange contact is less abrupt than the SST wheel profiles and does not exhibit two point contact – this will help minimise rail wear.

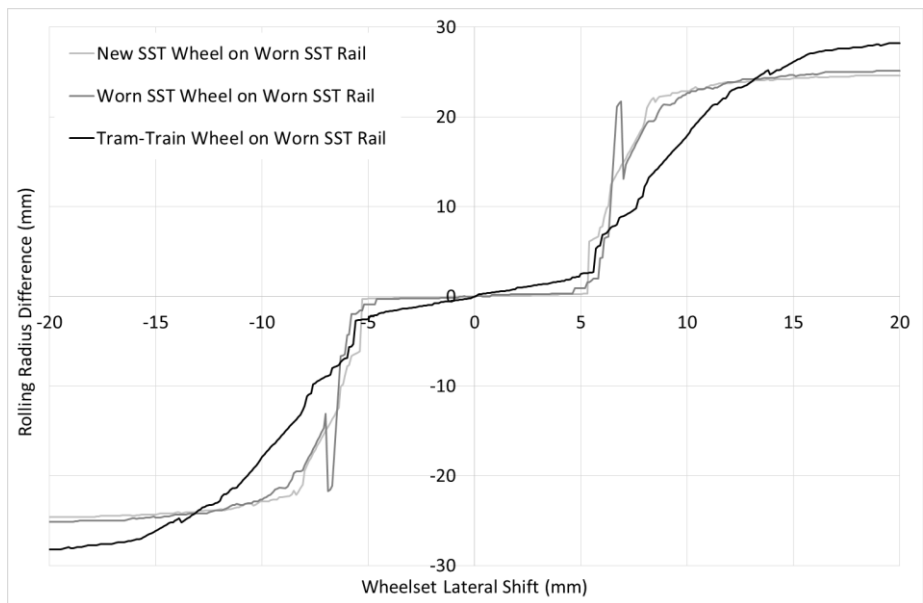


Figure 11: Rolling Radius Difference plot on SST infrastructure

Contact angle

The contact angle is the angle of the contact patch relative to the horizontal plane. The contact angle can be considered as a measure of flange climb derailment resistance. A steeper flange contact angle maintains a lower risk of flange climbing [9]. Figure 12 presents a plot of contact angle for new and worn SST wheel profiles and the Tram-Train profile on SST infrastructure

The plots show that as the profiles enter flange contact, the maximum contact angle reached tends towards the wheel profile design flange angle. For the current SST profile that

angle is 76° and for the developed Tram-Train profiles, the angle is 68° - the same as a BR P8. The plots also show the distance over which the angle is maintained in terms of wheelset lateral shift, with a larger lateral shift being more favourable as this offers the greatest protection against flange climb.

For all of the Tram-Train profiles developed, the flange angle is reached and sustained without a significant rate of reduction in flange angle as the contact patch moves up the flange. This characteristic provides sustained flange climb protection under more demanding contact conditions.

The flange angle of the SST tram profile is higher than the BR P8 and the Tram-Train profile and therefore offers greater resistance to derailment than the developed Tram-Train profiles. Whilst the flange angle of the Tram-Train profile is reduced in comparison to the SST profile, there is significant operating experience of such flange angles in tight radius curves on other light rail systems [11].

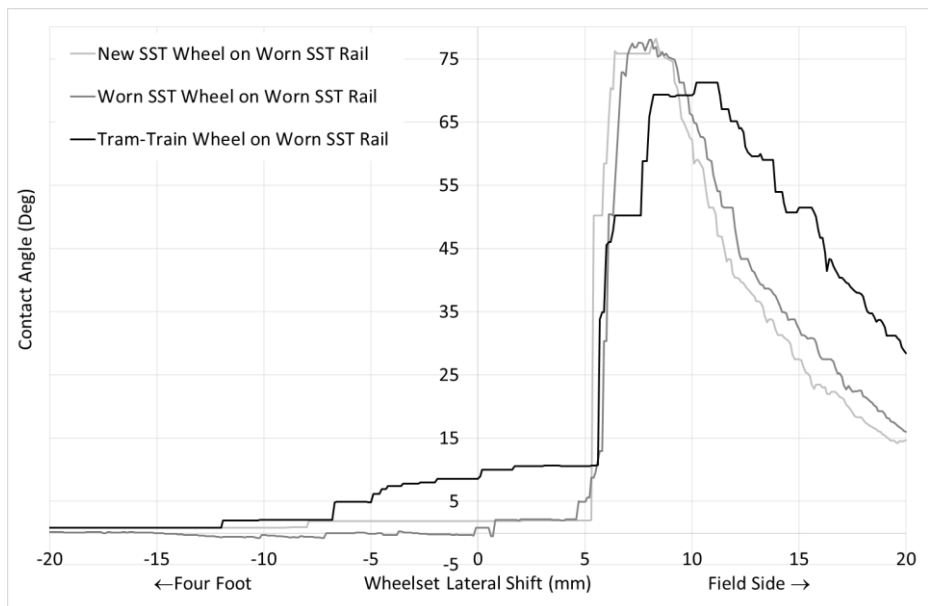


Figure 12: Contact Angle plot for right wheel on SST infrastructure

Contact patch area

It is desirable to maximise the contact patch area in order to reduce the stress in the wheel/rail contact patch. Increased levels of contact stress can result in greater damage within the wheel/rail interface in the form of wear, rolling contact fatigue (RCF) [12,13] and rail squats [14]. Higher contact stresses will also cause increased levels of wear and could possibly cause plastic flow of material within the wheel and rail. The aim of this aspect of the study was to develop a new Tram-Train profile with similar or greater contact patch areas than the existing profiles on the SST and NR systems. Figure 13 shows that although the contact patch area is slightly smaller on the flange for the Tram-Train profile on SST infrastructure, the contact patch area is similar overall to the current SST wheel profiles.

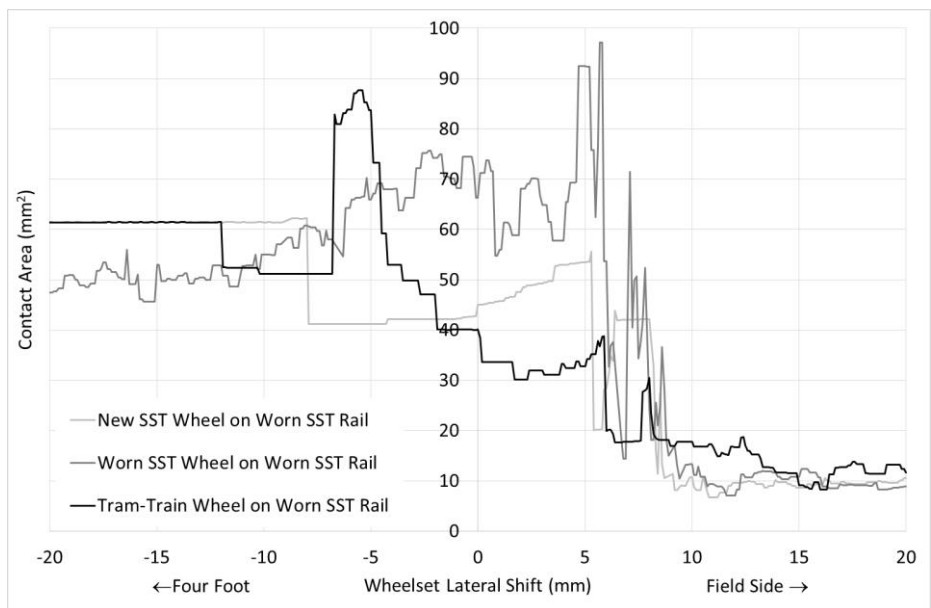


Figure 13: Contact Patch Area plot for right wheel on SST infrastructure

Equivalent conicity

Equivalent conicity provides a further indication of the vehicle’s curving performance and lateral stability. The conicity values of existing SST and NR wheel/rail combinations have been calculated and are used as a benchmark for the levels of conicity which the Tram-Train vehicle should accommodate without increased risk of lateral stability issues. Table 3 presents the equivalent conicity values for the different wheel/rail combinations on the Tram-Train route. The conicity values have been calculated using the UK method for a lateral shift of 2.5mm [15]. It can be seen that the conicities generated by the Tram-Train profile do not exceed the maximum conicities generated by the SST and NR wheel/rail profiles (the maximum value is underlined).

Table 3: Equivalent Conicity values for different profile combinations

Wheel	Rail				
	55G2	39E1 1:40	SST Worn	56E1 1:20	NR Worn
P8 New	--	--	--	0.174	0.103
P8 Worn	--	--	--	0.264	0.163
SST New	0.338	0.083	0.024	--	--
SST Worn	0.264	<u>0.352</u>	0.066	--	--
Tram-Train	0.23	0.201	0.22	0.185	0.13

Dynamic Curving Simulations

The VAMPIRE Curving Analysis program was used to assess the curving performance of all profile combinations. The simulations were carried out using a coefficient of friction of 0.45 on the tread and flange and were run at balancing speed – the speed at which the lateral forces from curving are cancelled out by the cant of the track. The vehicle model used for these simulations was representative of a complete Tram-Train vehicle in crush laden condition with inflated suspension.

The outputs from the simulations were the $T\gamma$ and the Contact Stress in the tread and flange contact patches.

$T\gamma$

$T\gamma$ is the work done or energy dissipated in the contact patch and provides an accepted method of quantifying the wear at the wheel/rail interface when used as an input parameter to the rail wear function developed by British Rail Research (BRR) [7]. Figure 14 presents this function and how it relates $T\gamma$ to a rail wear rate.

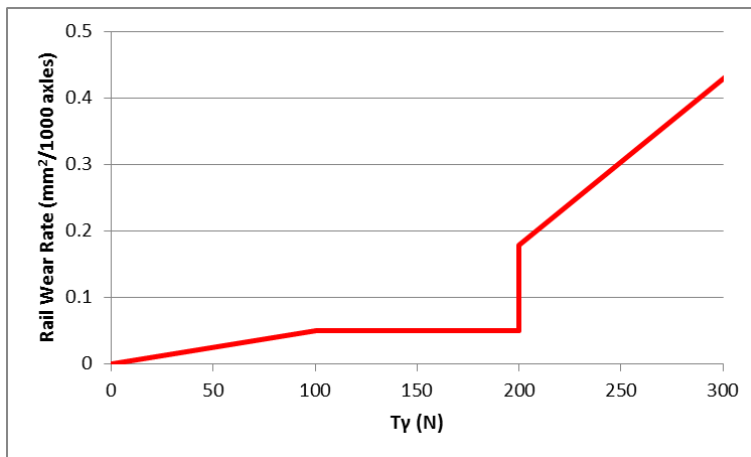


Figure 14: British Rail wear function

The wear function shows that higher $T\gamma$ values equate to higher levels of wear, consequently it is desirable to minimise the levels of $T\gamma$, an approach which has been taken in this study. Figure 15 shows a typical plot of total high rail $T\gamma$ for a range of curve radii. This shows new and worn SST and the Tram-Train wheel profiles on worn SST rails. It can be seen that the worn SST wheel generates much lower $T\gamma$ values than the new SST wheel on curve radii greater than 150m. The Tram-Train profile performs in a similar way to the worn SST wheel profile, with both showing which demonstrates good performance on the worn SST rails.

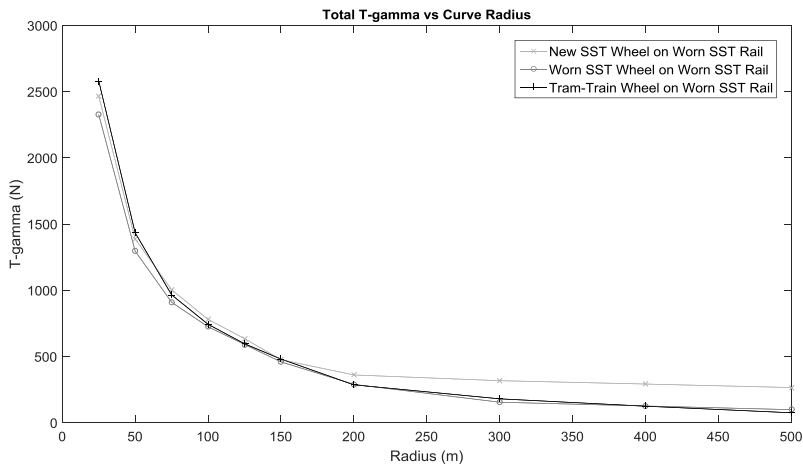


Figure 15: Total High Rail T_γ vs Curve Radius for Supertram Infrastructure

Contact stress

The contact stress calculation is linked to the contact area calculated in the contact conditions section but the calculation of contact stress takes into account the effect of the dynamic forces generated by curving and the distribution of loads between tread and flange contact patches. It is also affected by the instantaneous contact angle, which governs the normal force between wheel and rail. Figure 16 shows how the contact stresses vary with curve radius for the Tram-Train vehicle on SST infrastructure. On the low rail tread the Tram-Train profile generates lower contact stresses than the new SST profile for all curve radii. On the high rail wheel tread the Tram-Train profile generates the highest stresses out of all the profiles at curve radii greater than 300m but the corresponding stress on the flange is below that of the new SST wheel until the curve radii drops below 200m.

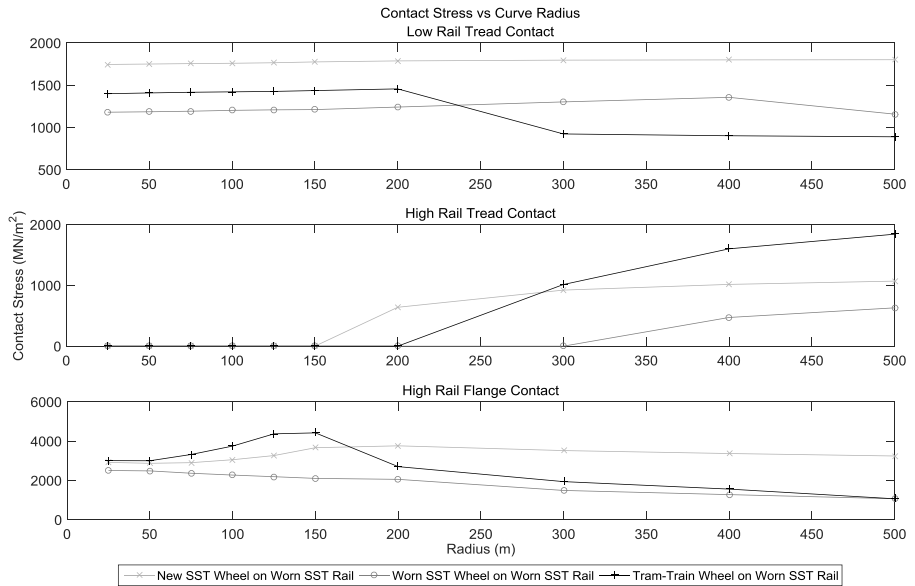


Figure 16: Contact Stress vs Curve radius for Supertram Infrastructure

Geometric Assessment

Safe passage of the Tram-Train wheelset through all trackforms and S&C has been confirmed through a series of geometric assessments and cross-dimensional proofs.

Grooved rail

When a vehicle is curving, the wheelsets will have an Angle of Attack (AoA) relative to the rails. This AoA creates a geometric effect which increases the effective wheel flange width. If the effective flange width is too great then both flange face and flangeback can come into contact with either side of the groove simultaneously; known as forcing of the wheel flanges in the rail groove. This scenario can pose an increased derailment risk and will also result in excessive wheel and rail wear.

The maximum effective flange width, or minimum permissible groove width, was calculated using the Filkins-

Wharton method [16]. The calculation was carried out using a computer code and a Nytram plot [16] was created to show the locations of the flange and flangeback contacts. Figure 17 shows the Nytram plot for the worst case – flange worn wheels, minimum back-to-back spacing and maximum track gauge. The points labelled ‘1’ identify the flange contacts on the high and low rails and the point labelled ‘2’ is the flangeback contact which would cause flange forcing. The point labelled ‘3’ highlights where keeper rail contact would occur and hence defines the minimum groove width required to prevent keeper contact. The minimum permissible groove width for the SST system was found to be 26.7mm which is far less than the 40.7mm groove width of new 55G2 groove rail. Therefore forcing of the flanges in grooved rail sections will not occur.

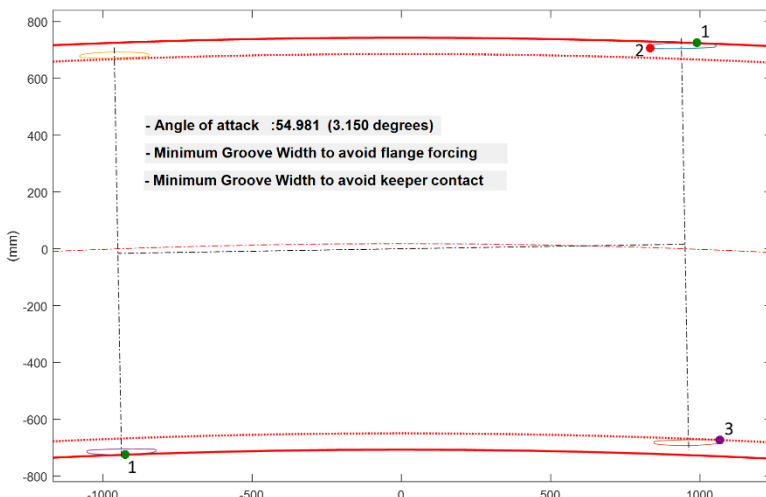


Figure 17: Nytram Plot

Switch and Crossing Interaction

In the absence of a single comprehensive design method, several approaches have been applied to ensure that the Tram-Train wheelsets safely negotiate S&C. These methods have been taken from BOStrab guidelines, Network Rail standards and EuroNorms.

Blade vertical overlap

BOSTrab clause 3.10.2 [17] looks at the switch toe and requires that the wheel flange overlaps the switch toe by a minimum of 4mm. Figure 18a shows the dimensions that must overlap, H and h. Figure 18b shows the Tram-Train wheel profile located at an NR full depth and shallow switch toe with 3mm of residual opening, demonstrating that the dimensions H and h provide an acceptable overlap of 6.8mm.

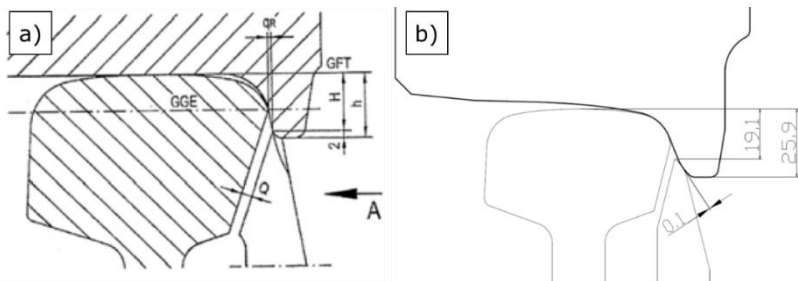


Figure 18: a) BOSTrab flange overlap b) Tram-Train profile at NR full depth switch toe with 3mm residual switch opening showing flange overlap

Minimum contact angle

This NR Standard for ‘Inspection and repair to reduce the risk of derailment at switches’ [18], states that as a general rule, the point at which the wheel-rail contact angle reduces to 60° should typically be no less than 20-25mm below the rail head (See Figure 19a). It also mandates that contact should not occur with the switch blade at an angle lower than 60° . This is to protect against flange climb derailment at the switch toes. Figure 19b shows the Tram-Train profile on an NR switch blade. The distance to the 60° point is greater than the 20mm minimum distance but the minimum contact angle does drop below 60° to 56.8° . This is however not considered a problem in this application, as the standard BR P8 profile, which has an excellent operational safety record, also fails to meet this requirement, with a minimum contact angle of 50.8° under the same conditions.

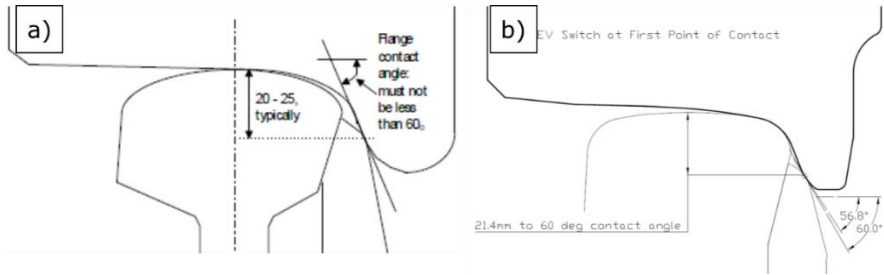


Figure 19: a) Minimum contact angle b) Tram-Train profile at first point of contact with NR Full Depth switch blade showing contact angles and positions

Secant contact angle

Secant contact occurs when the wheel encounters an object on its route – in this case the end of the switch toe. EN 13232-9 [19] states that contact with the switch toe should not occur in the contact ‘danger zone’. This assessment protects against flange climb and switch splitting derailment.

The standard defines the ‘danger zone’ as the area around the flange tip where the contact angle is less than 40° , Figure 20a shows an example of a safe contact condition with the ‘danger zone’ highlighted. Figure 20b shows the Tram-Train wheel profile located at the proposed NR switch toes with 3mm of residual opening. The ‘danger zone’ is highlighted in red and extends through an angle of 80° around the flange tip. It can be seen that the wheel flange does not contact the switch toes at any point within the defined sector and therefore the Tram-Train profile meets the requirements in this assessment.

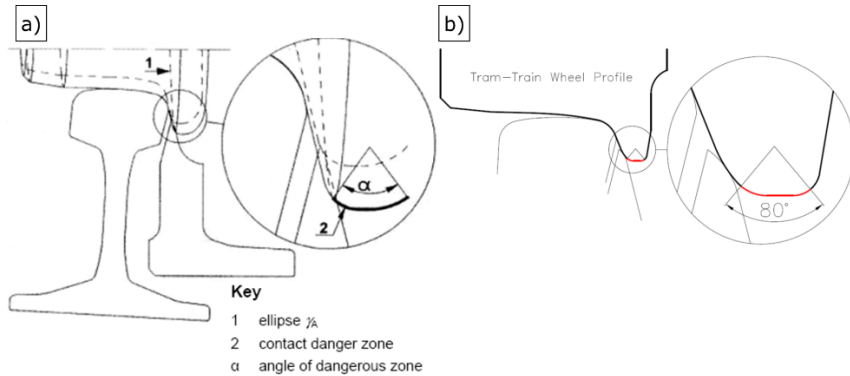


Figure 20: a) Secant contact angle b) Tram-Train profile at NR full depth switch toe with 3mm residual switch opening showing 'Danger zone'

Check Rail Interaction

The Tram-Train profile design required a cut-out in the flangeback to provide a checking face at 1379mm back-to-back spacing for compatibility with SST grooved rail whilst also retaining a checking surface further up the flangeback with a spacing of 1360mm for compatibility with NR S&C. The cut-out extends up the flangeback to a height which was selected to ensure that the wheel profile can operate safely on SST grooved rail even when the rail head reaches its vertical wear limit. It is noted that provision of a flangeback step reduces the effective minimum wheel radius with respect to the wheel turning limit and hence ultimately there is slightly reduced wheelset life over a conventional flangeback wheelset. This factor was also considered when designing the geometry of the step.

The provision of a flangeback cut-out raises the checking face for NR infrastructure further up the flangeback, therefore NR check rails must be raised to maintain correct and safe contact conditions with the Tram-Train profile flangeback. As the lift takes the check rail beyond the standard NR structure gauge, route gauging clearance is required for all vehicles running on the NR section of the Tram-Train route to

ensure that no part of a passing vehicle could contact the raised check.

Figure 21 shows the check rail in the nominal and raised position. The minimum amount that the check rail should be raised is 40mm to bring the vertical checking surface of the check rail in line with the NR checking surface on the flangeback.

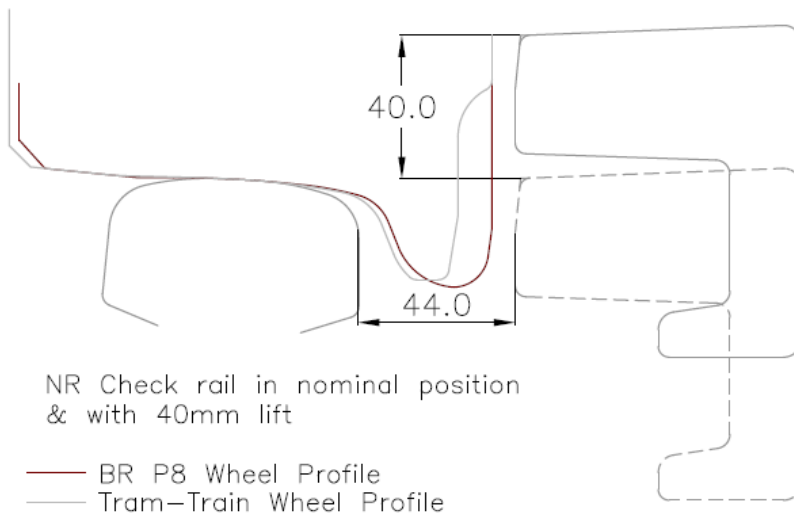


Figure 21: NR Check rail in nominal and raised position

Whole Route Simulations

Whole route simulations were carried out on the Tram-Train route using the proposed new Tram-Train wheel profile and the existing NR and SST profiles. The simulations used a vehicle model that is representative of a complete Tram-Train vehicle in both tare and crush laden conditions with inflated suspension allowing the behaviour of the different wheel profiles on each infrastructure to be compared. The simulations were separated between NR and SST route sections to enable direct comparisons with the dominant wheel profiles on each route.

Wear

The results from the whole route simulation were processed to provide an estimate of rail wear rate. This was performed by converting the calculated $T\gamma$ (T-gamma) to an estimated wear rate using the British Rail Research division wear model [7] described previously. Tare and laden results were combined to give a more realistic wear rate.

Figure 22 and Figure 23 show the predicted wear rates on SST and NR infrastructure respectively. The x axis defines the distance along the track and the y axis the predicted wear rate in terms of the area of rail cross-section lost per 1000 vehicle passes.

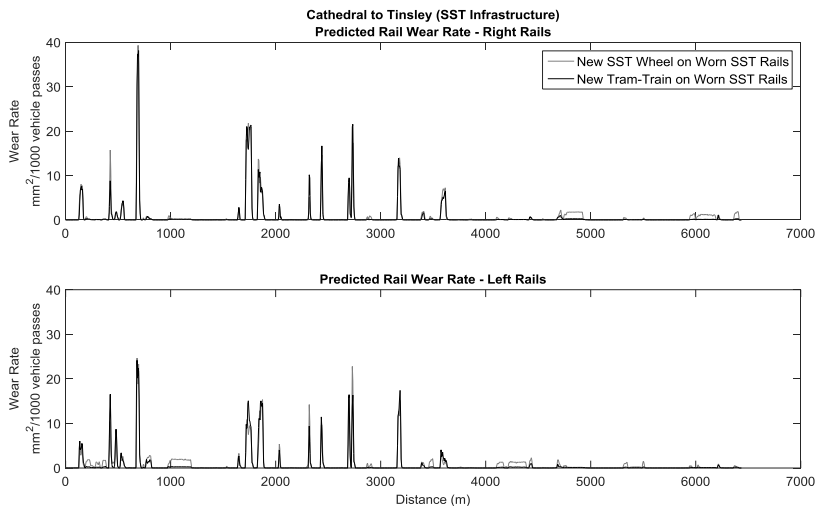


Figure 22: Predicted wear rates on SST infrastructure

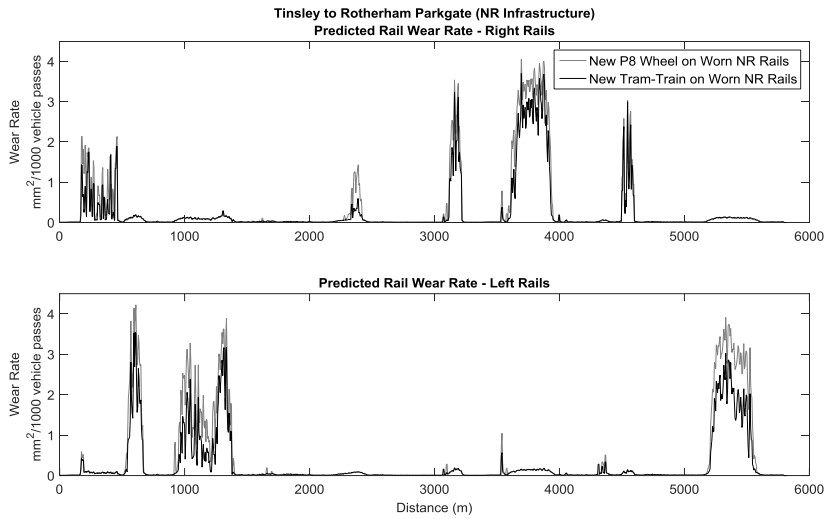


Figure 23: Predicted wear rates on NR infrastructure

Figure 24 shows the total wear rate over the SST and NR sections of the infrastructure. The total wear has been normalised against route mileage to provide a valid comparison between SST and NR sections of the route. With the exception of new SST rails, the proposed Tram-Train profile generates lower levels of wear when compared to the wheel profiles currently operating on the route. In the case of new SST rails, the proposed Tram-Train profile generates slightly more wear than the current SST profile, however this scenario will revert to the worn case as any new infrastructure wears towards the steady-state worn rail shape.

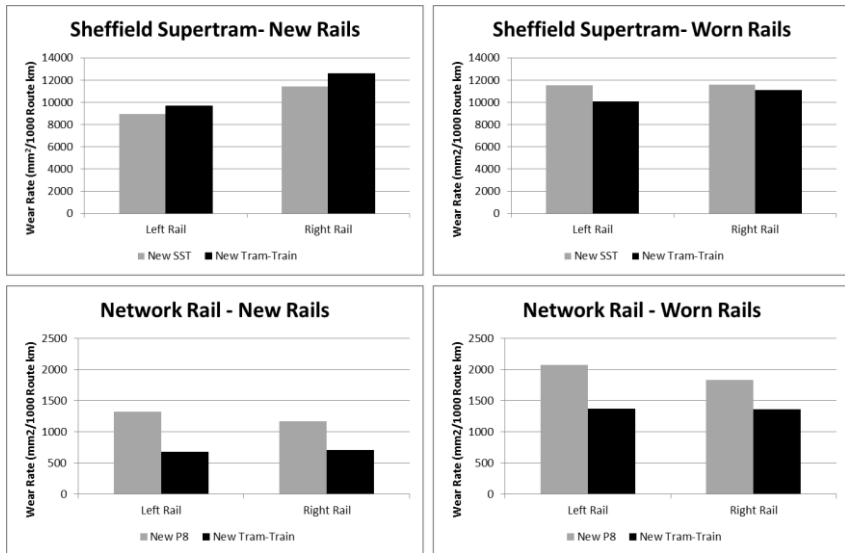


Figure 24: Total wear rates normalised against route kilometers

Rolling Contact Fatigue

The results from the whole route simulations were also processed to provide an indication of the likelihood of rolling contact fatigue occurring (RCF) on the rails. To predict RCF, the Whole Life Rail Model (WLRM) was used [20,21]. This model relates $T\gamma$ to RCF damage and returns an RCF Damage index. Tare and laden results were combined to give a more realistic wear rate. Figure 25 shows the RCF Damage function applied in the study. The function has a range between $T\gamma$ values of 15N and 175N where RCF damage is generated. Above a $T\gamma$ of 175N wear occurs and RCF damage is removed.

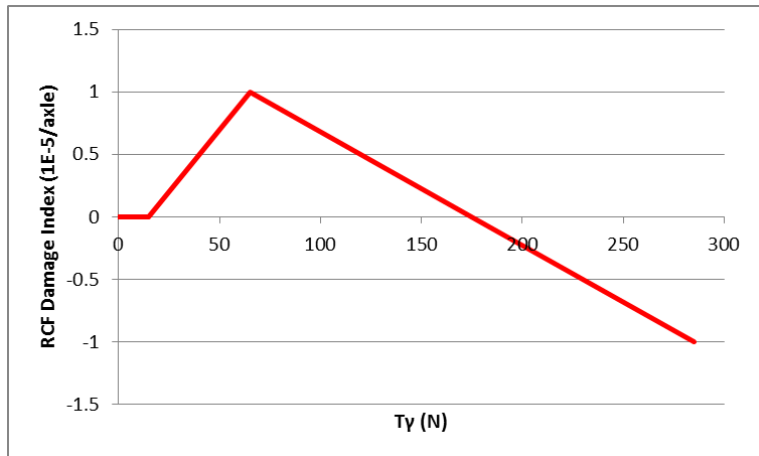


Figure 25: Whole Life Rail Model RCF Damage Function

Figure 26 and Figure 27 show the predicted RCF damage rates on SST and NR infrastructure respectively. The x axis defines the distance along the track and the y axis the RCF damage accrued per vehicle pass. An RCF damage index of 1 indicates crack initiation.

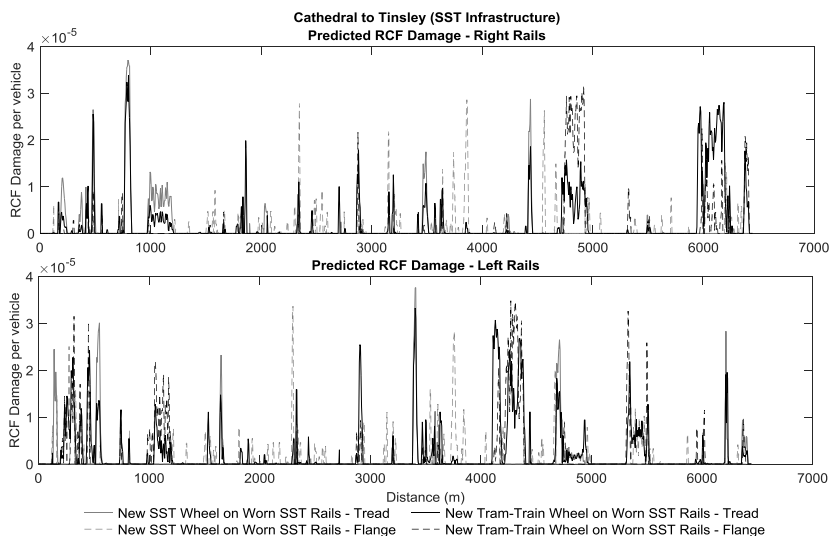


Figure 26: Predicted RCF Damage rate on SST infrastructure

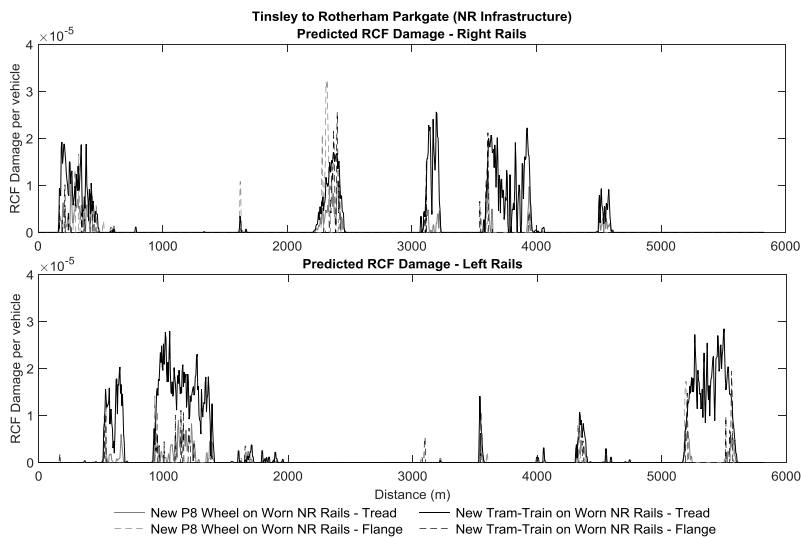


Figure 27: Predicted RCF Damage rate on NR infrastructure

On SST infrastructure, it can be seen that the proposed Tram-Train profile and the SST profiles generate similar peak values of RCF damage. There are a number of peaks where one profile generates more damage than the other and this is a result of the differing curving performances of the SST and Tram-Train profiles.

On NR infrastructure the peak RCF damage values are of a similar magnitude for the Tram-Train and BR P8 wheel profiles, however, there are many peaks predicted with the Tram-Train profile where the predicted damage for a BR P8 is zero. This is again due to the different curving behaviour of the two profiles; The better curving performance of the Tram-Train profile means that the $T\gamma$ values generated in curves are lower putting them in the RCF damage generation section of the WLRM whereas the $T\gamma$ values generated by the BR P8 are in the wear regime part of the function.

The predicted $T\gamma$ values are only indicative of whether the new profile will have a substantial impact on RCF on the SST and NR route sections as they do not consider the contribution that the other traffic on the route will make to the

route RCF damage levels. To fully assess the change in RCF damage, post Tram-Train introduction, it would be necessary to model all vehicle types on the route and sum the RCF damage generated by each vehicle pass. However, as the Tram-Train vehicle will form only a small proportion of the total traffic on each system, it is not considered there will be significant impact on the RCF damage on either SST or NR systems.

Conclusions

A dual operation wheel profile has been designed to run on Network Rail and Sheffield Supertram infrastructure. The design incorporates several features to meet the requirements of the two rail systems such as:

- Cut-out in the flange back to provide two checking surfaces for compatibility with NR check rails and SST grooved rails
- 68° flange angle with bespoke flange toe profile to provide required clearance for safe passage through NR switch toes
- Flat flange tip to facilitate flange tip running through SST diamond crossings
- Tread geometry derived from the BR P8 profile that avoids hard two-point contact, reduces wear and improves curving performance

The work has shown that it is possible to design an effective dual operation wheel profile even when the rail profile shapes encountered on the light and heavy rail sections of the route are very different. Through an iterative process of stepwise refinement and assessment, the wheel profile tread geometry has been developed to provide a level of performance in terms of contact conditions, rail wear and vehicle behaviour that was similar or better than the current SST and NR profiles. This ensures that the new Tram-Train profile will not have any significant impact on the asset life of

the two infrastructures. The new Tram-Train profile provides the following characteristics:

- Rolling Radius Difference and conicity levels that do not exceed current wheel/rail combinations in order to prevent vehicle stability problems
- Contact stresses that do not exceed current levels
- Sufficient resistance to derailment
- $T\gamma$ levels that do not exceed current levels
- Reduced wear rates when compared to current profiles
- Indicative RCF levels that are not excessive when compared to existing profiles

A full geometric assessment has been undertaken to ensure the new profile can safely negotiate all of the track features found on NR and SST infrastructure including:

- Grooved rail
- Check rails and Guard Rails
- Switches with residual switch opening
- Common crossings
- Diamond crossings (including flange tip running crossings)

During the development of the profile it was identified that the check rails on NR infrastructure would need to be raised to allow the new wheel profile design to work. As part of the geometric analysis, a minimum check rail height of 40mm above the running rail was defined.

The final wheel profile design is illustrated in Figure 28.

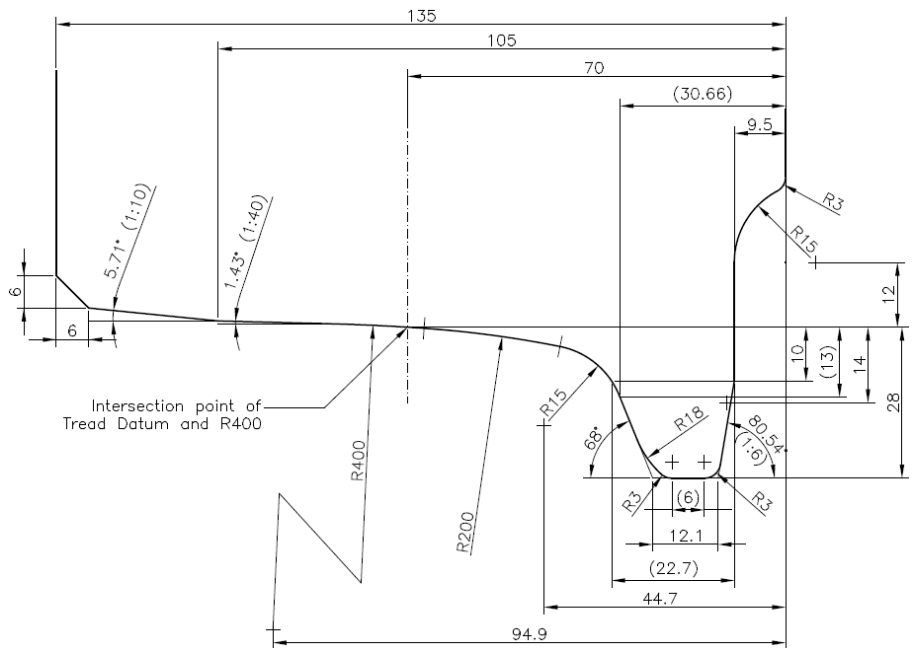


Figure 28: Final Tram-Train wheel profile

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