Influence of Rail Surface Geometry on Wear and Service Life of Crossing Rails

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Abstract: Malfunctioning components on railroads can lead to the decrease of efficiencies. Switch frog is costly, but has a short service life. However, for safety reasons, regular inspection is necessary. Determining the service life helps to plan maintenance, as well as renewal of the switch frog, in an easy and timely manner. This study aims to determine the geometry model and the influence of it's relevant parameters, for predicting the service life of switch frogs, based on the measured data of 13 switch frogs. The data were provided by DB Systemtechnik GmbH, Germany. Using the relationship between contact pressure and vertical wear area the model will be performed. In this study, the geometry of the wing rail is also considered, because it affects the change in the geometry of the frog tip. The deviation between the measurement data and the model could be minimized by calibrating the model results with the measured data in order to achieve higher accuracy. As an outcome, the service life of switch frogs will be determined, and the optimal initial geometry identified. In future studies, the model needs to be modified, to predict the remaining service life, for the case of any non-initial geometry.

Keywords: switch frog; geometry; service life; wear

1 Introduction

Crossing is a superstructure, which allow rail vehicles to travel from one track to another without interrupting the journey. Without this component, there would be no train station and rail networks [1]. Crossing is a moving part, so it is a safety relevant component. During operation, the crossing component must be setup in the right position so that the train can travel flawlessly with allow velocity. If these requirements are not fulfilled, the derailment of the wheels or a railway accident may occur.

Owing to the report form German Railways, the number of passengers in long-distance transport is expected to reach 200 million, the freight train is expected to reach 68,700 Mio.tkm in 2027 [2]. If the rail network not expands to cover future demand, the traffic load in system (Mt) will force the infrastructure components to reach their limits more quickly and maintenance or renewal must be accomplished without compromise.

Furthermore, in 2022 and 2023, 75% of long-distance trains have to pass at least one construction site and its speed has to slow down so that approximately two thirds of all ICE and IC trains reached their destination on time. Without developing highly loaded network to high performance network, the punctuality will continue to get worse in the future. In aspect of the new construction, expansion and maintenance of tracks, these takes time and investment. Installing a new switch in the rail network has various processes, namely design of the switch profile to correspond to the track curve, manufacture, transportation and on-site assembly [3]. Especially during installation, there is undeniable passenger or track capacity restrictions due to track blockages [4].

From an economic perspective, as the replacement of a turnout or individual turnout components is always associated with high costs. In [1] is stated that, the price of the turnout is about 1% of overall Investment costs. However, in aspect of maintenance cost the ratio of turnout is more than 25% of overall maintenance costs. To minimize maintenance costs, DB Systemtechnik GmbH in Germany has launched a research project concentrated on two areas: materials and structure [5]. These two factors have an effect upon the service life, as represented in the following relationship [6]:

$$lifetime \leftrightarrow \frac{resilience}{strain}$$

Resilience represented the strength of the material. If the material is hardwearing, the lifetime is lengthened. The strength has directly proportional to the service life. For example, using the chromium bainite steel in highly stressed area of the switch frog yield positive evaluation [7] [8]. Even in the maintenance of tramways austenitic filler metals can be considered as an alternative rail welding technique [9]. However, the hard-wearing one comes with high investment expenditure. The critical criterion is, weather this high quality one can prolong a service life in order to achieve lower life cycle cost than the low quality one. It was suggested that the longest service life might not be the most efficient option, on the contrary, it would be would be preferable to optimizing the geometry to provide the optimum service life and achieve the lowest life cycle costs [10-12]. If the turnout longer in operation the annually fixed costs will reduce whereas the variable costs increase due to the maintenance program.

A further consideration is the strain or contact pressure (σ), which is the ratio between wheel force and contact area. Contact pressure relate to deterioration process, damage on running surface and change in geometry.

In a previous study [13], the iteration model for determining new geometry and service life of switch frog is performed corresponding to the reality phenomenon by using initial measurement geometry which are provide by DB Systemtechnik GmbH as input data. As a result, latest geometry and anticipated service life of the switch frog is determined. The purpose of this study focuses on the sensitivity of the parameters in the geometry model, which can prolong the service life and minimize life cycle costs of switch frog at the same time.

Once the rail profile is known, it would not only be beneficial to know the fatigue condition and position, but also to be able to apply the appropriate maintenance program to prolong the service life of switch components. In various studies, such as the examining the relation between rail geometry and the service life [14], analyzing fatigue damage and predicting service life based on various vehicle conditions [15], examining a crossing design to reduce the impact load and damage as well as reducing life cycle cost [16], it provides experts to predict the service life of turnouts.

In addition, in some studies explained, the utilizing image processing method that can investigate actual fatigue status on rolling surface and predict the damage and its location on switch frog up to about 10 Mt in advance [17]. Another image processing method describes the use of a semantic segmentation method to detect cracks in rail surface with better economic efficiency by maintaining inspection accuracy [18]. These can help professionals to make precisely decision by rail surface inspection. Moreover in some studies the height of the wing rail and effect on the touchdown position are also considered to realign the model with the actual situation [11, 19, 20].

2 Materials and Methods

Begin with the initial measured geometry, the service life will be derived at the end of iteration. To make the Model precisely the calibrating with measurement data from DB Systemtechnik GmbH is necessary. The switch frog material in the study is R 350 HT, geometry profile is EW-500-1:12 laid in in facing move direction, all samples are located in Haste, Germany.

This model are construct using simply mathematic model as shown in Figure 1. All sub-models are integrated with each other through a Matlab program. Each sub-model can be later modified afterwards to achieve a better results and correlation between measured and calculated service life. Furthermore, additional considered parameters can be placed into the sub-model later, which allows the program to approach the reality scenario and yield more accurate outcome.

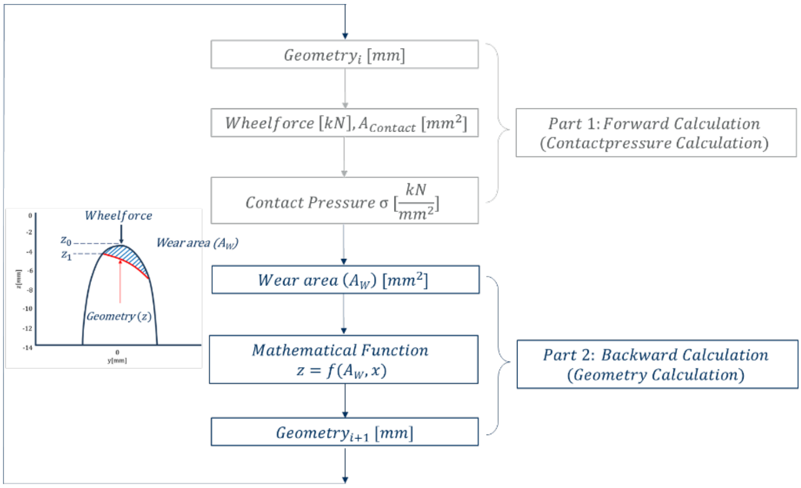

Figure 1

Flow-chart of the wear simulation process

In various studies such as [21-23] applied the rail profile update in their studies to predict damage in turnouts. The methods differ in details but the concept of rail update is used, the more frequent the update, the better the result. By the way, it comes with high computational cost and time. The actual Geometry ($Geometry_i$) will be replaced by the new one ($Geometry_{i+1}$) which correspond the reality that rail profile change due to the traffic load.

The model Concept use the initial Geometry as input in part 1 (forward calculation) to determine wheel force and contact pressure. This part derived from the cause and effect and measurement systems which occur in running surface during the degradation process [6] [24]. When the contact pressure (σ) is determined, it will be integrated in next 2 sub-models. The first one is used for calculating the rail contact fatigue in model part 1, because contact pressure leads to damage in switch frog surface[25]. The degree of damage, which indicates the running surface status, gradually climbs from 0 on the first iteration. Once this value is greater than 1, this indicates that the running surface is broken and corresponds to the end of the service life. For this reason, the service life will be calculated in relate to contact pressure.

The second sub-model is the wear area ($\overline{A_W}$) model. The contact pressure (σ) will be applied to compute the total wear area (A_W). At each cross section (Figure 3) A_W will be use to compute new geometry ($z = f(A_W, x)$). Wear area (A_W) consist of 2 components. The first one is deformation area (A_D) which occurred in run-in phase, the second one is wear area (A_W) which occurs in wear phase.

At the beginning of the operation, most of total wear areas are from the deformation part (A_D). The contour line of switch frog is deformed from the original position in this phase. After that in wear phase, the contour line and the height will gradually decrease in relation with wear area rate ($\overline{A_W}$) and traffic load ($B\ [Mt]$). The area of A_D and A_W are illustrated in Figure 4.

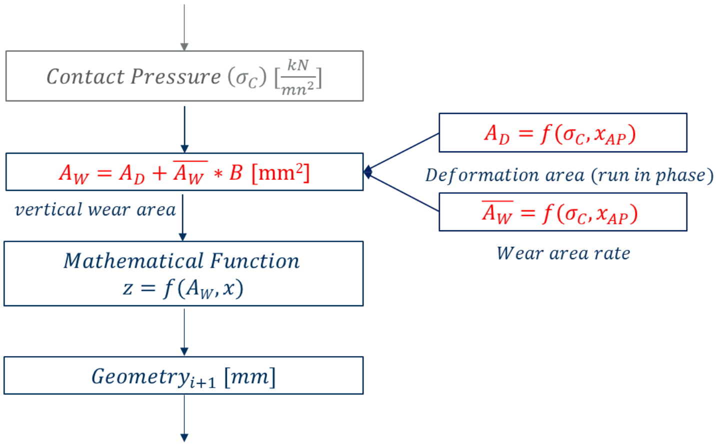

Figure 2

Influence of the factors (contact pressure, position) at vertical wear area

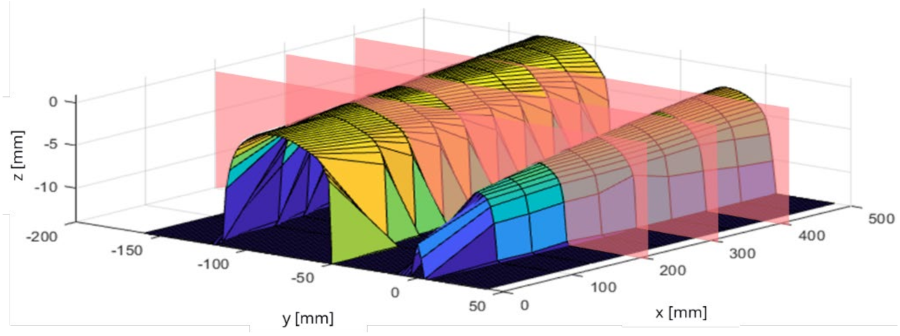

Figure 3

3D-Modell of switch frog and its cross section (x = 0 mm to 500 mm) [6]

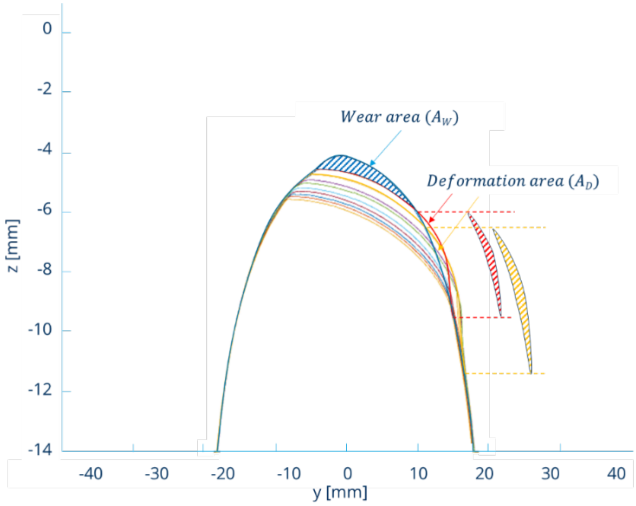

Figure 4
Deformation area and wear area

To compute the new Geometry ($Geometry_{i+1}$)the mathematical Model is constructed by using A_W. As shown in Figure 5 the new geometry is function of A_W and position of x in longitudinal direction.

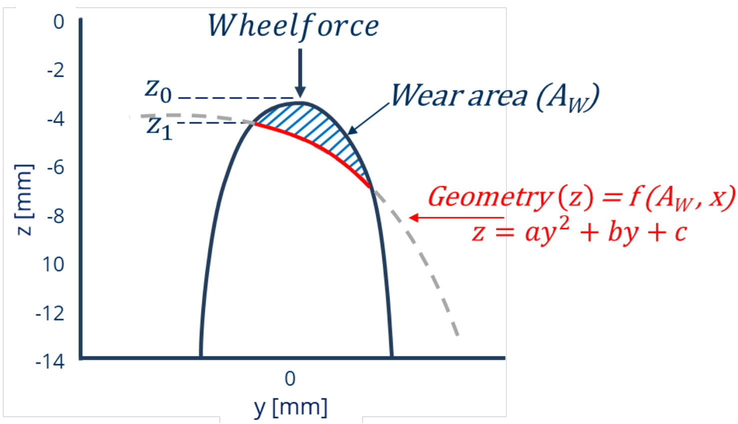

Figure 5
Mathematical function of frog-rail cross section and wear area

In the next iteration loop the $Geometry_i$ will be replaced by the new one $Geometry_{i+1}$. Consequently, contact area (A_C) and contact pressure (σ) will be changed due to geometry update in part 1 in next iteration. At the end of the new iteration $Geometry_{i+2}$ will derive. This process repeats until the damage index reaches the threshold value and the lifetime is derived.

In this study the parameter to construct mathematical function will be scrutinized. To find the variables that have a decisive effect on lifetime and to design an optimal geometry that provides the longest service life. There are 4 parameters that use in mathematical function in above diagram, namely $\overline{A_W}, a, b, c$ which affect the geometry ($z = f(\overline{A_W}, a, b, c)$). The relation is represented in Figure 5. In this study only the parameters of the frog tip are examined.

To examine the sensitivity of each Parameter. Each parameter will be adjusted in the same range (+-10% of non-changed value). The deviation can be computed by compared the service life with the normal one that derived from non-changed parameter.

3 Results and Discussion

The following diagram demonstrates the results for 4 considered parameters, which affect the $Geometry_{i+1}$ directly, these will be used as input for the next iteration in Part 1.

3.1 $\overline{A_W}$ and Service Life

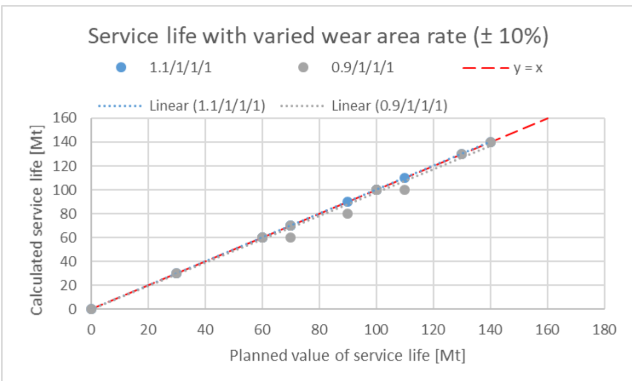

Figure 6
The service life of turnout with 90-110% of vertical wear area rate

The expression "-/-/-/-" in Figure 6 indicate the value of each parameter ($\overline{A_W}/a/b/c$) that will be regulated in model. $\overline{A_W}$ $[\frac{mm^2}{Mt}]$ in dicate the change of wear area $[mm]^2$ per load unit [Mt]. Figure 6 shows the divergence of service life, when wear area rate ($\overline{A_W}$) is about 10% more (1.1/1/1/1) or less (0.9/1/1/1) than normal value and the results show small difference of service life when wear area rate ($\overline{A_W}$) about 90%-110% of original value.

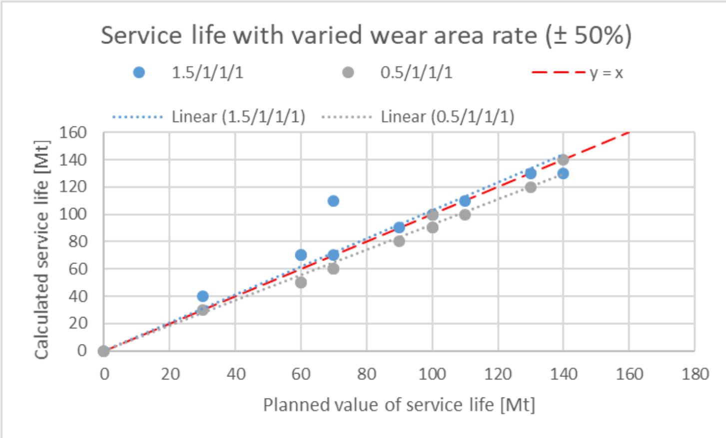

Figure 7
The service life of turnout with 50-150% of vertical wear area rate

However, in Figure 7 the range of $\overline{A_W}$ is wider from 50% (0.5/1/1/1) to 150% (1.5/1/1/1), the change is rather noticeable.

3.2 "a" and Service Life

The range of parameter "*a*" is about 10% more (1/1.1/1/1) or less (1/0.9/1/1). In comparison to ($\overline{A_W}$) the deviation from the original service life can be obviously seen in range of 20%.

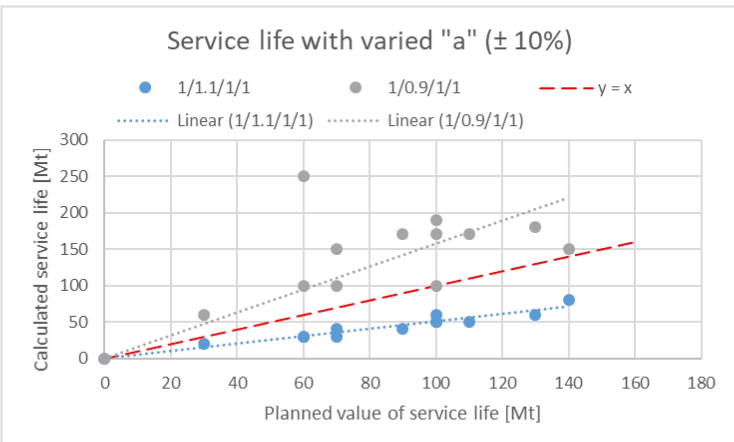

Figure 8
The service life with respect to the varying parameters a

This deviation from red line (Fig. 7 and Fig. 8) indicates the influence of the parameter on the service life. From the two diagrams it can be assumed that the parameter “a” has a strong impact on the service life than the wear area rate ($\overline{A_W}$).

Nonetheless, it can be seen that with the same planned value of service life, such as at 60 Mt, the service life of the flatter curvature (90%*a) can rise to 100 Mt and 250 Mt. The reason for these deviation could arise from the initial geometry. The different initial geometry causes both different heights and different contact surfaces, which is responsible not only for the contact pressure but also for the degree of damage in the first iteration. With a greater degree of damage in the first iteration, it is reasonably assured that this running surface will reach its limit before the lower one. Another reason could be the distribution of the touchdown point, which influences the accumulated damage degree on the running surface. If the touchdown point has a widely distributed, the damage area will be broader, which can slow down the deterioration of this position before it reaches its limit.

3.3 b, c and Service Life

Parameter b indicates the inclination of the parabolic contour line (z) in Figure 5 which relates to A_W and x. Parameter c is the height of parabolic contour line (z). "c" is the calibrated value so that the wear area $A_W[mm^2]$ in previously sub-model and wear area between $Geometry_i$ and $Geometry_{i+1}$, that derive from mathematical model, are identical. Since the new geometry is a function of Wear area(A_W), it is necessary that the wear area between each $Geometry_i$ und $Geometry_{i+1}$ corresponds to A_W which is derived from contact strain(σ).

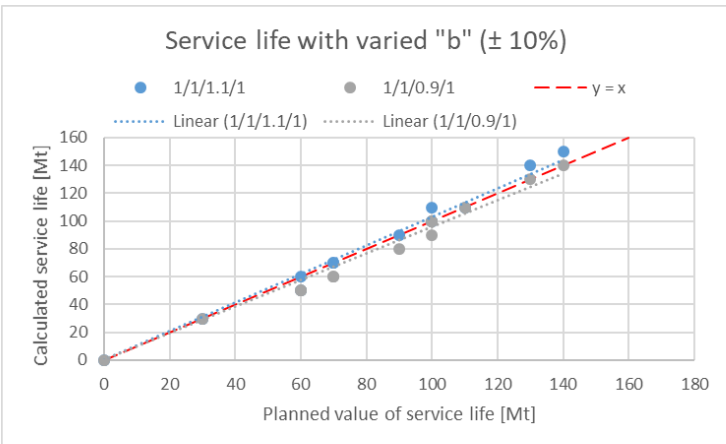

Figure 9

The service life with respect to the varying parameters b

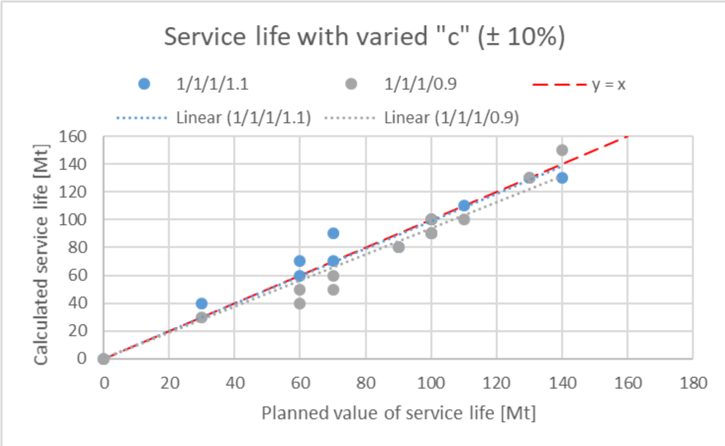

Figure 10

The service life with respect to the varying parameters c

Figures 9 and 10 show that both b and c hardly have an impact on service life, due to the small deviation from the computed service life.

The following tables demonstrate the correlation coefficients between normal service life from normal (non-changed parameter) and various scenarios and the sensitivity of considered parameters.

Table 1

Correlation coefficients with normal scenario

Scenario	$\overline{A_W}$ +10%	$\overline{A_W}$ -10%	a +10%	a -10%	b +10%	b -10%	c +10%	c -10%
correlation coefficient	1.000	0.994	0.965	0.623	0.994	0.992	0.977	0.980

In Table 1 most all correlation coefficient have a high correlation with the base Scenario, except the case of $a - 10\%$.

Table 2

The Sensitivity of variables

Scenario	$\overline{A_W} \pm 10\%$	$\overline{A_W} \pm 50\%$	a ± 10%	b ± 10%	c ± 10%
$\Delta\mu_i$	0.2	1.0	0.2	0.2	0.2
Avg. Sensitivity	0.13	0.17	6.04	0.35	0.68

The sensitivity analysis can be derived by determining ratio between the difference in service life ($\Delta SL/SL$) and the difference in each parameter($\Delta\mu_i$). The sensitivity of each variables are defined as follow $\frac{\Delta SL/SL}{\Delta\mu_i}$.

The average sensitivity of all 13 samples represents that the parameter “a” has the highest deviation (6.04), which means that the service life of the switch frog is most strongly influenced by parameter a. These correspond with diagram in Figure 8. The more distance between the computed point and red dashed line, the higher the influence of parameter on the service life.

In Figures 6 and 7, $\overline{A_W}$ hardly has an impact on service life. From measured Data the highest wear area also take place in deformation phase or run-in phase. Due to the equation $A_W = A_D + \overline{A_W} * B$, the amount A_D (deformation wear area) has a strong impact over $\overline{A_W}$ in run-in phase. This means that the small change in the wear area rate ($\overline{A_W} \pm 10\%$) has a slightly effect on the overall wear area when the transport load ($B[Mt]$) is low and has a low impact to service life, even if “z” is a function of A_W. The service life of $110\%\overline{A_W}$ are higher than the normal one. It can be that faster wear rate seem like a grinding process so that the cracks on running surface is removed. On the one hand, this can help to prolong the service life, on the other, can also reduce the rail mass.

Both “b” and “c” are horizontal and vertical shifting direction of the contour line. Their impacts are higher than $\overline{A_W}$ but still lower than “a”. That would be implied that the contour line shift has minor effect neither to increase nor to decrease the contact area. Hence, the contact strain does not fluctuate as much as it is in the case of “a” and so does the service life.

The geometry’s equation is defined as follows;

$$z = ay^2 + by + c \qquad (1)$$

The parameter “$2a$” derived from the second order differential equation ($z'' = 2a$) and in practically “$2a$” is a curvature of frog tip. Comparing the sensitivity of “a” with others parameter, it is obvious that 20% change of "a" has the strongest influence to the turnout’s lifetime.

When “a” is about 110%*a (•), the service life of all samples when compares with the original one are decreased. A larger "a" designates a smaller contact area(A_C), thereby the contact strain (σ) will be larger and leads to higher deformation are (A_D) in the run-in Phase. Consequently, the damage zone has a higher degree of damage than in the normal case, when the equivalent traffic load are considered.

On the contrary, a flatter curvature (90%*a) increase the service life. In Figure 8, all grey points (•) are above the red dash line. The flatter curve provides a larger contact surface between wheel and rail. Therefore, contact strain (σ) and damage on the frog tip is slowly and gradually increasing and the damage degree in run-in phase is not as high as in normal case. Consequently, the service life of the frog tip is also extended. To sum up, the smaller “a” is, the broader the contact point, and the longer the service life.

Conclusions

The Switch Frog is one of the most important components for railroad operation. For safety reasons, regular inspection is necessary for the proper use of switch frogs.

Both for determining the service life and for applying an objective evaluation [26] [27] to indicate the condition of rail damage and predict rail failure in advance, helps the specialist in making a precise decision, concerning which maintenance program should be considered. As a result, minimizing life cycle costs can be expected.

This study utilized a geometry model and the influence of its relevant parameters, to determine the service life of, and identify the optimal initial geometry of Switch Frog. The results demonstrated that the three parameters have minor impact on the deviation of lifetime. Except in the case of the curvature$(2a)$. With only a 20% change, the sensitivity is quite high, while comparing with the 3 other parameters. It should be considered that a smaller "a" value provides the longer life. Since a smaller "a" directly affects greater running surface and results low contact strain, so the initial damage is decreased. Ultimately, this extends the service life.

A following study will focus on the optimization and the implementation of the “a” value (percentage of “a”) in practice. Therefore, manufacturers can develop a new initial geometry, to prolong service life and minimize life cycle costs at the same time. Furthermore, the model needs to be modified, as the amount of measured data increases to correspond with a more varied geometry, as well as the trailing direction.

Acknowledgements

I would like to acknowledge Dr.-Ing Ulf Geber. I would also like to thank Franziska Kluge. I would like to express my thanks the DB Systemtechnik GmbH for the measured data. I would like to express my gratitude to Office of Educational Affairs The Royal Thai Embassy.

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Nomenclature

$Geometry_i\ [mm], z[mm]$	The height of frog tip's and wing rail's contour line in the vertical axis
$i\ [-]$	Number of iterations
$A_D\ [mm^2]$	Deformation area
$A_W\ [mm^2]$	Vertical wear area
$\overline{A_W}\ [\frac{mm^2}{Mt}]$	Vertical wear area rate, the wear area per load capacity unit
$B\ [Mt]$	Load mass
$\sigma_C\ [\frac{kN}{mm^2}]$	Contact pressure
$x_{AP}\ [mm]$	The position of touchdown point
a, b, c	Polynomial coefficients
$\Delta\mu_i$	the deviation in percent of the considered parameter
$SL\ [Mt]$	Service life of switch frog