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INFLUENCE OF WHEEL PROFILES ON ROLLING CONTACT FATIGUE AND WEAR RATE OF RAILWAY WHEELS

Nebojša Bogojević[1], Vojkan Lučanin[2], Bojan Tatić[1]
bogojevic.n@mfkv.kg.ac.rs

[1]Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac,
Dositejeva 19, 36000 Kraljevo,
[2]Faculty of Mechanical Engineering, University of Belgrade,
Kraljice Marije 16, Beograd,
SERBIA

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Abstract: *Wheels and rails provide guidance of a rail vehicle on a track. For that reason wheels and rails have dominant influence on safety against derailment and running performance of a railway vehicle. The wheel and the rail profiles also have significant influence on the wheel/rail wear, surface damage, forces in the contact between wheel and rail, track shift forces, as well as on track and wheelsets maintenance. This paper presents the influence of different combinations of wheel and rail profile on rolling contact fatigue and wear rate of rail wheels. Simulations behaviors of a vehicle were performed for six different combinations of wheel and rail profiles with different rail inclinations, on straight track and in a curve, assuming ideal track without track irregularities. The set of combinations includes theoretical profiles of wheel and rail S1002/UIC60i40, S1002/UIC60i20 as well and worn profiles P8/UIC60i40, P8/UIC60i20, WP4/BV50i30 and WP4/MB1BV50.*

INTRODUCTION

In the last decade railway transport became more reliable, faster, more frequent and cheaper. Increasing of railway vehicle speed and wheel loading leads to the increased problems connected to the wheel and rail damage. Therefore the maintenance process and costs are increased [1], [2].

The higher speed and wheel loading causes that wear and rolling contact fatigue problems appear more frequently. Increased wear rate and faster damage of the rail and wheel may lead to speed limitations, decrease of wheel loading, decrease of vehicle running safety and increase of maintenance costs. In this way, understanding and prediction of the wear rate and rolling contact fatigue-RCF may be very important in order to decrease the maintenance cost and to improve vehicle design as well as wheel and rail profile design [3][4].

Wheel/rail contact occupies an area with the size less than a coin, and that contact transfers the load from wheel to track in the range from 4 tones (passenger vehicle) to 30 t (heavy haul freight vehicles). Considering small contact area and high forces which are present in the contact, high material removal is expected. Because the load and material removal repeat many times, the possibility of surface damage on wheel and rail is present.

From the first cylindrical wheel profile on the flat rail, many different wheel and rails profiles are made. During the time, the wheels profiles were changed, first to conical, and further to present complex profiles, in constant effort to increase the vehicle stability, safety and to increase their life. Parallel with development of wheel profiles rail profiles are correspondingly changed, so today we have several different rail profiles with complex geometry.

Since 1970, ORE and later UIC and EN committees attempted to introduce one standard wheel profile in the Europe, which will be optimized for low wear and RCF. Due to the different rail types, track gauges, rail inclinations which exist in the Europe, the definition of such type of wheel profile was very difficult. The wheel profile named S1002, based on the German DB II wheel profile, is designed for UIC 60 rail profile and rail inclination 1:40 [3].

Several optimized wheel and rail profiles exist in European countries, due to different rail track geometry, operation conditions and vehicle design. In the last years the UIC 60 rail profile is mainly present in the railway track in European countries.

Several researchers in the past years have tried to optimize the wheel and rail profile [3], [4]. Due to different approaches, parallel to S1002 wheel profile today are known several wheel profiles such as P8 – mainly in UK, WP4 – wheel profile for freight vehicle, for iron ore transport in Sweden.

METHODOLOGY

Wear represents removal of material from the rail head or the wheel thread and flange at the contact surface. The removal of the material may be caused by motion of the material from the contact region or by removing the material by adhesion. Both processes lead to change of the wheel and rail profiles.

The main request for railway vehicle designers is that vehicle has good ride quality and safety on straight track and in the curves. Significant influence on the vehicle behavior has equivalent conicity. Equivalent conicity λeq is defined as the quotient of rolling radius change and relative lateral displacement.

Lower equivalent conicity on tangent track leads to better lateral stability and safety performance on tangent track, while higher values of the equivalent conicity lead to better bogie steering in curves. The equivalent conicity depends on the wheel and the rail profiles as well as on the change of the track gauge.

In this paper we will assume that the wear rate is proportional to the energy dissipation in the wheel/rail contact [10], [11], which can be expressed over wear index $T\gamma$:

$$T\gamma = F_\xi \frac{V_\xi}{V} + F_\eta \frac{V_\eta}{V} + M_\zeta \frac{\omega}{V} \quad [Nm/m], \tag{1}$$

where are: $F\xi$ - creep force in longitudinal direction, $V\xi/V$- creepage in the longitudinal direction, $F\eta$ - creep force in lateral direction, $V\eta/V$- creepage in the lateral direction, ω/V spin in the contact.

According to the [6], the influence of spin creepage and moment of the spin to the energy dissipation in wheel/rail contact may be significant.

Rolling contact fatigue represents damage of the surface of wheels and rails that can be explained as initiation of the crack and crack propagation. RCF may be estimated on the basis of the vertical and lateral forces in the wheel/rail contact, creep forces and creepage in the wheel/rail contact, characteristics of the material in the contact. Measurement of these parameters is not possible with present measurement equipment. Multi–body simulations and FEM calculations are today mainly used for prediction of the wear and RCF.

Several factors have influence on surface crack formation on the rail: operating conditions, e.g. train speed, type of rolling stock, axle loads; track lay-out and track geometry parameters, e.g. curve radius and super elevation; rail material properties. External factors, such as temperature or humidity or even existence of the water in the wheel-rail contact can accelerate the crack propagation process. Phases of the surface contact fatigue are:

- Crack initiation,
- Crack propagation,
- Crack spreading over thread and flange surface.

The wheels, as well as the rails, are exposed to RCF, especially when vehicle is running in the curves. When the vehicle is running through a curve, the outer rail and the inner leading wheel are exposed to higher wear and RCF, see Fig 2.

Prediction of the RCF of the rail and wheel can be made using shakedown theory, or by calculation of the surface and subsurface indices [10].

In this paper, the influence of the different wheel/ rail profiles on the RCF will be estimated using surface fatigue index FI_{surf} and subsurface fatigue index FI_{sub}, developed by Ekberg at all [10].

Initiation of the crack and its propagation on the surface of the wheel and rails may be expressed by surface fatigue index. The surface fatigue index is result of the low-cycle fatigue and material ratcheting and it may be expressed as:

(2) $FI_{surf} = \mu - \frac{2abk}{3F_z}$, The surface fatigue will occur if $FI_{surf} > 0$.

Subsurface fatigue index gives estimation of the crack initiation on depth more than 3 mm, as a result of the high cycle fatigue. From equation (3) it can be seen that this index depends on the vertical load and the size of the contact area.

(3) $$FI_{sub} = \sigma_{EQ} \approx \frac{F_z}{4\pi ab}\left(1+\mu^2\right) + a_{DV}\sigma_{h,res},$$

the fatigue damage will occur if it is fulfilled following condition:

(4) $$FI_{sub} \geq \sigma_{EQ,e},$$

where are: F_z - vertical force in the wheel-rail contact, a,b - semi-axes of the Hertzian contact patch, k - yield stress in pure shear, σ_{EQ} - equivalent stress, a_{DV} - material parameter, $\sigma_{h,res}$ - hydrostatic stress, $\sigma_{EQ,e}$ - fatigue limit. More details about surface and subsurface index and RCF estimation it can be found in [10].

VEHICLE MODEL

Prediction of the RCF and wear rate of the wheel has been performed on the model of the freight rail vehicle based on the Fanoo040 wagon used for transportation of the iron ore in the north part of Sweden. The weight of loaded wagon is 120 tons with maximal running speed of 60 km/h. Vehicle is equipped with the three-piece bogie Amsted Motion Control M976 with load sensitive friction damper. The friction damping is modeled with Saint-Venant elements [8], [9]. All nonlinearities which appear due to gaps, contacts between stiff elements, slip-stick motion and nonlinear characteristics have been considered in the model. More about vehicle model and model validation can be found in the reference [7].

Due to high axle load, 30 tons per axle, the presented vehicle is very sensitive to wear and RCF. The quarter of the vehicle model has been shown on the Fig. 1.

In this study, the model of the vehicle has been improved by introducing wrap stiffness in the three-piece bogie in order to represent realistic behavior of the vehicle in the curve. More data about wrap stiffness of the three-piece bogie may be found in [8], [9].

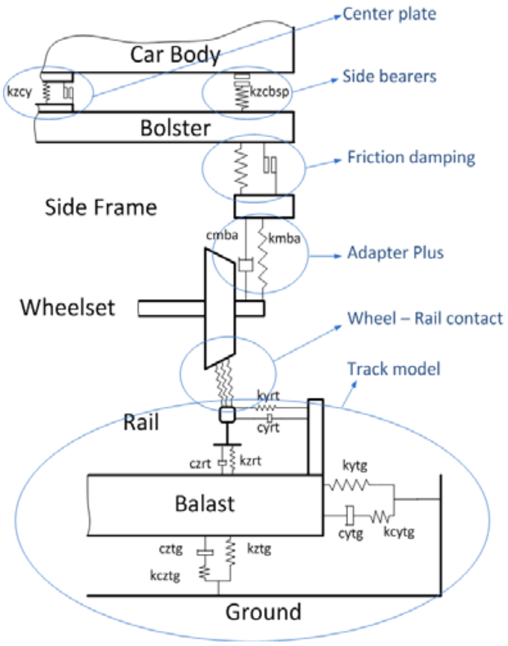

Fig. 1 Model of the vehicle

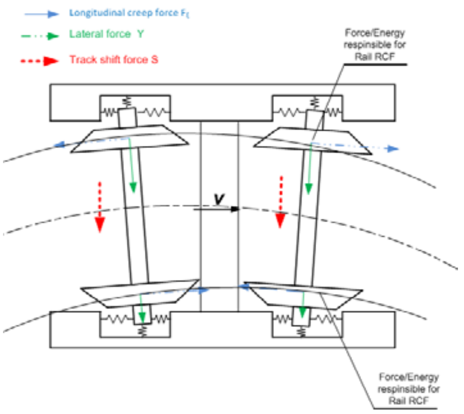

Fig. 2 Energy that causes the rail and wheel damage

TRACK MODEL

The model of the track takes into account ground, ballast, rails and the stiffness between these bodies as it is shown in Fig 2. By changing the characteristics of the springs and the dampers in the model, can be modeled the tracks with wooden and concrete sleepers, as well as different track stiffness. For example, track stiffness during summer and winter can be modeled in that way.

Simulations for the wear and RCF estimation are performed on the track with variable curve radius and track cant, as it is shown in Table 1.

Table 1. Geometry of the curves chosen for simulation

Curve No.	Curve radius [m]	Cant [mm]
1	300	112
2	376	83
3	476	60
4	700	40
5	1000	30

WHEEL-RAIL CONTACT

The contact geometry and the creep forces are calculated based on the non-linear Hertzian theory. The wheel-rail contact has been modeled using Gensys KPF function. The KPF function has possibility to describe the contact between wheel and rail with 3 points simultaneously.

For each wheel-rail combination the wheel/rail function has been calculated, and then the wear rate and RCF have been estimated for track geometry described in Table 1. In the simulations, the influence on the wear rate and RCF has been estimated for the following combinations of the wheel and rail profiles: S1002/UIC60i40, S1002/UIC60i20, P8/UIC60i40, P8/UIC60i20, WP4/BV50i30 and WP4/MB1BV50.

S1002uic60i40 is recommended wheel-rail combination by UIC and EN committees. Serbian railways use s1002uic60i20 wheel-rail combination. In the UK are used the optimized P8 wheel and uic60 rail profiles. In order to achieve profile resistant to the wear and RCF on the track for iron ore transportation, the optimized wheel profile WP4 and Swedish bv50 rail profile is used. In the curves, the outer rail has optimized mb1 profile.

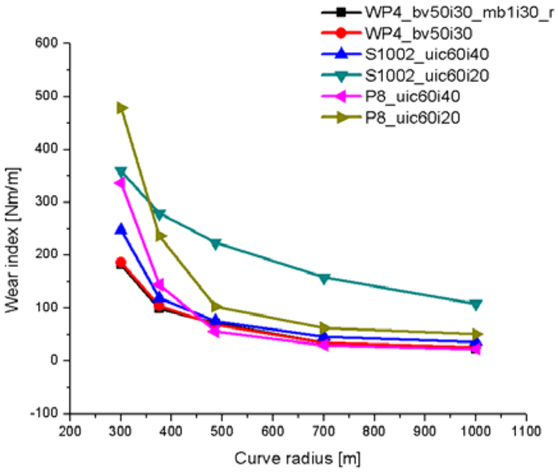

Fig. 3 Wear rate

From Fig.3 it can be seen that wheel/rail combination wp4_bv50_mb1i30 has the lowest wear index, which means that this combination has very stable profiles and low maintenance. Due to lower values of the equivalent conicity, the wheel/rail combination ENS1002_uic60i20 and P8_uic60i20 has bigger lateral movement-slipping over rail heads. The lower equivalent conicity for these two wheel/rail combination causes worse bogie steering, which leads to higher slipping in longitudinal direction. The bigger slipping in the lateral and longitudinal direction causes high values of the wear.

ROLLING CONTACT FATIGUE

The wheel rail combinations P8uic60i40 and S1002uic60i20 are less sensitive on the surface crack initiation than other wheel rail profile combination. It is interesting that optimized WP4bv50mb1i30 wheel-rail combination is very sensitive on the surface crack initiation, see Fig. 4.

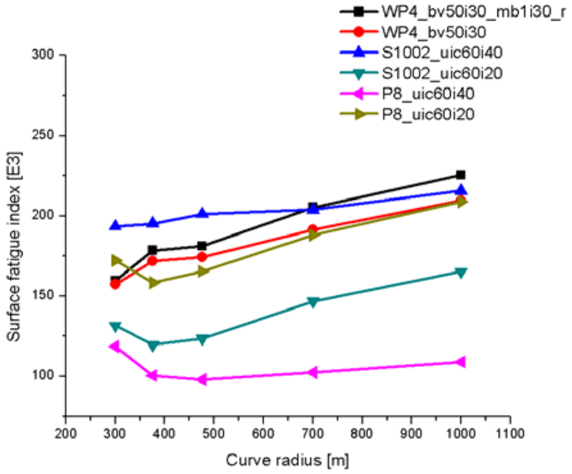

Fig. 4 Surface fatigue index

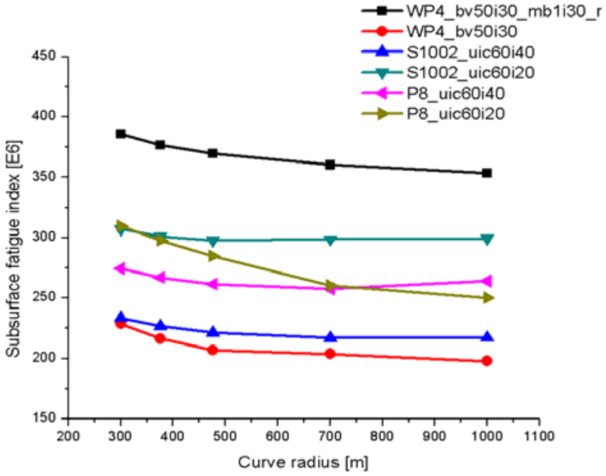

Fig. 5 Subsurface fatigue index

The highest sensitivity on subsurface fatigue has optimized wheel-rail combination WP4bv50mb1i30. The lowest sensitivity on this type of RCF has standard S1002uic60i40 and optimized WP4bv50i30 wheel-rail combination. From achieved results it can be seen that optimized profile WP4bv50mb1i30 and WP4bv50i30 have low wear rate and require low maintenance process of the wheel and rail regarding to wear.

However, high sensitivity on fatigue damage of this combination of wheel-rail profiles requires high attention during the exploitation. The wheel-rail profiles S1002uic60i40 recommended by UIC are sensitive on surface fatigue damage and resistant to the wear.

The wheel-rail combination used in Serbia, S1002uic60i20, has relatively high wear rate and low sensitivity to surface and subsurface fatigue damage. Higher wear rate can prevent initiation of the crack on surface. However, the high wear rate of wheels and rails require a higher level of maintenance.

CONCLUSION

The study has shown that optimized wheel-rail profiles have low wear rate and high sensitivity to RCF. On the other side, the profiles recommended by UIC are sensitive to wear and less sensitive to fatigue damage. It is important to note that wear rate and RCF depend on type of the rolling stock, as well as on vehicle suspension system. The assessment of wear and RCF in this study was given for heavy haul rail vehicle with high axle load.

Ideal combination of wheel and rail profiles, which will fulfilled all requirements, does not exist. However, future optimization of the profiles for freight and passenger rail vehicle may provide significant improvements of existing profiles.

Future work should be focused on analysis of the railway vehicles with various rolling stock and suspension system, for example vehicles with two axles and vehicles with Y25 bogies.

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ВЛИЯНИЕ НА ПРОФИЛА НА КОЛЕЛАТА ВЪРХУ КОНТАКТНАТА УМОРА ПРИ ТЪРКАЛЯНЕ И СТЕПЕНТА НА ИЗНОСВАНЕ НА ЖЕЛЕЗОПЪТНИТЕ КОЛЕЛА

Небойша Богоевич[1], Войкан Лучанин[2], Боян Татич[1]
bogojevic.n@mfkv.kg.ac.rs

[1]Факултет по машиностроене и строителство в Кралево, Университет в Крагуевац, Доситейева № 19, 36000 Кралево,
[2]Факултет по машиностроене, Университет в Белград, Кралийце Марийе № 16, СЪРБИЯ

Ключови думи: *колело, релса, профил, RCF, износване, динамично поведение*

Резюме: *Колелата и релсите направляват движението по релсовия път. Поради тази причина те имат доминиращо влияние върху надеждността срещу дерайлиране и ефективността на движение на железопътното возило. Профилите на колелата и релсите също така имат значително влияние върху износването колело/релса, повърхностните дефекти, силите в контакта между колелото и релсата, силите на изместване на пътя, както и върху поддръжката на релсовия път и колоосите. Статията представя влиянието на различни комбинации от профили на колелата и релсите върху контактната умора при търкаляне и степента на износване на железопътните колела. Направени са симулации на поведението на железопътното возило при шест различни комбинации от профили на колела и релси с различни наклони на релсите, при движение в прав участък и в криви, допускайки идеален релсов път. Наборът от комбинации включва новите профили на колелата и релсите S1002/UIC60i40, S1002/UIC60i20, както и износени профили P8/UIC60i40, P8/UIC60i20, WP4/BV50i30 и WP4/MB1BV50.*