

Influence of train axle load on wheel-rail interface friction

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Abstract. The implementation of high speed railways in India are in their early phases and vast studies are being conducted for the effective implementation of the system. Maintaining the traction required for efficient operation of trains at high speeds requires the net minimum frictional coefficient to be maintained at the wheel-rail interface, across the desired range of axle loads and target speeds of train operation. With the increase in speed, wheels of the train tend to lift-off, effectively reducing the interface friction at the wheel-rail contact. In this study, the effect of increasing the axle load on the effective frictional coefficient available at wheel-rail interfaces during high speed railway operations were quantified by numerical simulations, and the results reveal that the net frictional coefficient available at the wheel-rail contacts have a trend to increase with an increase in the applied axle loads. Conversely, this instead points out that decreasing the axle loads for achieving higher speeds of train operation will result in reduction of traction, and there will be chances of wheel-slips on the rails during rapid acceleration and emergency braking situations. Modifying the rail surface friction using top-of-rail friction modifiers are a much easier alternative to making amendments in the wheel-rail profiles, for maintaining sufficient traction on rails. In the wheel-rail interfaces with high friction, lubrications in the boundary regime, mixed lubrication or hydrodynamic lubrication are applied on the basis of Stribeck curve, adopting the optimum frictional coefficients for avoiding rolling contact fatigue and high rates of wear due to plastic deformations. When there is less frictional grip, a coating of top-of-rail positive friction enhancers becomes necessary, for increasing the adhesion characteristics and achieving positive creep. This study emphasizes the importance of optimizing the contact at wheel-rail interfaces, to maintain the frictional coefficients to neither cause loss of traction due to lower grip, nor be on the higher side to cause rolling contact fatigue and high rates of material wear.

1. Introduction

Friction at the wheel-rail interfaces in railway operations play a significant role in maintaining sufficient traction, for running trains with safety and to have the ability to accelerate, decelerate or brake the train at specified locations on the railway track. In railway operations with high interface friction, rolling contact fatigue and rail deformations are commonly observed, accompanied by an increased rate of material wear in the wheel and rail sections. Higher levels of motive power are also required from the locomotives, to overcome the high forces of frictional resistance. This results in excessive wastage of motive power at high axle loads. In the cases where net frictional coefficients are lower than the optimum, wheel-slips occur during rapid acceleration of trains and wheels skid over the rails during emergency braking situations. The key aspect for operational safety of trains is to maintain an optimum coefficient of friction at the wheel-rail interfaces, at about a value of 0.35 [1]. When the



operational conditions imposed by the combination of railway loading and rail profiles deliver non-optimum coefficients of friction, friction modifiers shall be used for maintaining the traction necessary for safe operation of the trains.

2. Numerical simulation of railway operations

Full-scale field testing of train operations at high speeds and axle loads are associated with financial constraints, and they consume ample time. Numerical analyses can prove to be an effective method for solution of such problems, where full-scale analyses prove to be infeasible. In this study, numerical analyses were run simulating train operations at speeds of 160 km/h, which is the maximum operational speed of a train running in Indian Railways on date (the operational speed of Gatimaan Express running between Delhi and Agra). The simulations were performed with train axle loads in the range of 20 – 32.5 tonnes, for analyzing the influence of axle load on the effective frictional coefficient available at wheel-rail interfaces. The selected range of axle loads cover the classes of trains from passenger trains (with maximum axle loads of 20.3 tonnes) to the trains proposed for operation in dedicated freight corridors of India (with maximum axle loads of 32.5 tonnes).

2.1. Geometric model assembly

The geometric model of the wheel-rail system was developed in numerical modelling software SOLIDWORKS, and the model assembly was further imported into software ANSYS for finite element analyses. The geometric model was developed on the basis of geometries and specifications given by Research Design and Standards Organisation (RDSO), under the Ministry of Railways in India, for the manufacture of axle and wheels in broad gauge coaches of Integral Coach Factory (ICF) design [2]. A linear section of IRS 52 rails were modelled for a rail length of 200 metres, and a rail spacing of 1676 mm was provided, in accordance with the broad gauge railway track layout in India. Coning of the rails were also considered, by an inward tilting of 1 in 20, as shown in figure 1.

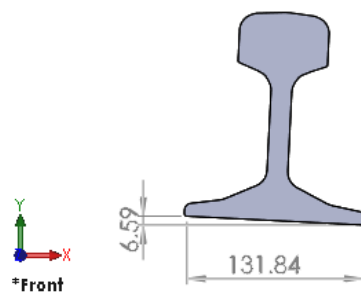


Figure 1. Inward tilting of rails by 1 in 20 (sectional view of left-hand-side rail).

The wheel-set was first assembled by mounting the wheels symmetrically on to the axle at a clear spacing of 1600 mm, in accordance with the RDSO specifications [2]. The wheel-set was further mounted on to the rails, aligning the wheels to travel in the forward direction of the rails, as shown in figure 2. The movement of wheels were allowed only in the longitudinal direction of rails, and the movements in the lateral and vertical directions were constricted.

2.2. Finite element modelling

The geometric model assembly was imported into finite element modelling software ANSYS, for conducting the tribological analyses. Structural steel was considered as the constituent material for both wheel-set and rails, with an ultimate tensile strength of 880 MPa and the material was considered to follow bilinear isotropic hardening behaviour. The numerical model was first optimized by considering the wheel-set as deformable bodies and rails as rigid, to overcome the large computational demands and time associated with the analysis of finely meshed lengthy railway track sections. The axle and wheels were assigned with SOLID187 elements, and the wheel-rail interface was modelled as

an asymmetric pair-based contact for simulating the high speed wheel-rail interactions. Contact surfaces in wheels were assigned with CONTA174 elements and rigid rail surfaces were modelled using TARGE170 elements.

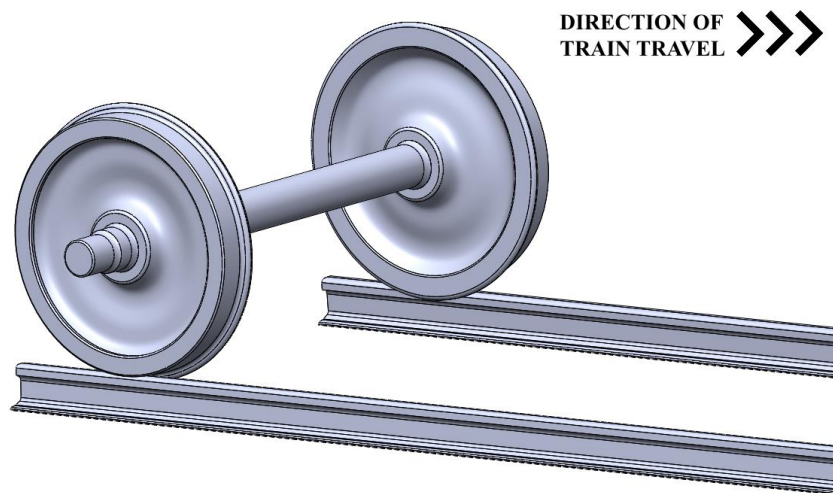


Figure 2. Assembly of wheel-set on rails (SOLIDWORKS).

Modelling the deformable nature of wheel-set allows computation of contact pressure and frictional stresses at the wheel-rail interfaces during high speed railway operations, under the influence of various axle loads. Based on the validation studies conducted by the authors, a solid mesh size of 27 mm was adopted for the wheel-set, and the contacting surfaces of rails and wheels were assigned with an ultra-fine mesh size of 1 mm for capturing the wheel-rail interactions with best accuracy.

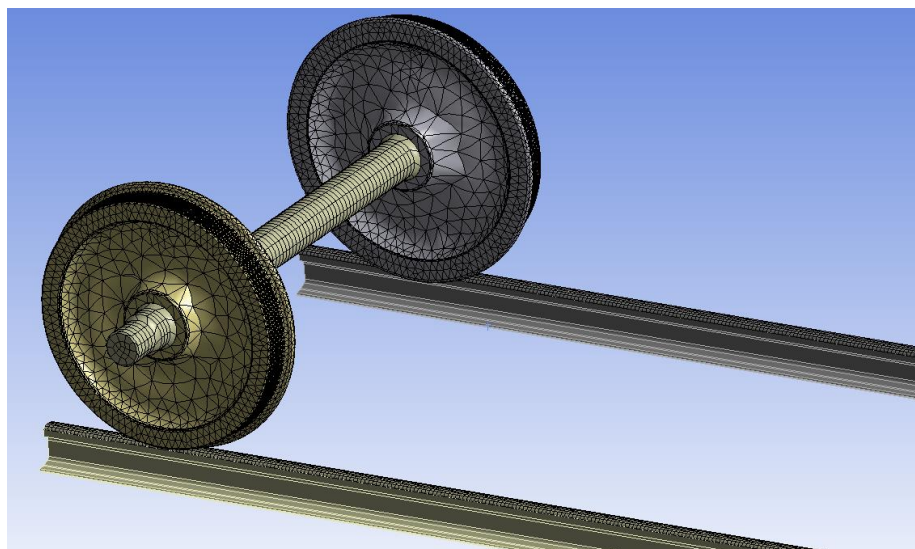


Figure 3. Finite element meshing of wheel-set and rails (ANSYS).

Augmented Lagrange formulation was used for solution of the contact interactions, and the stiffness was set to update at each iteration for simulating dynamic wheel-rail contact interactions. The coefficient of friction at the wheel-rail interface was set as the variable parameter during model analyses, for studying the effect of train axle load on the effective friction available at the wheel-rail interfaces during high speed railway operations.

2.3. Loads and boundary conditions

In the finite element model, bottom surface of the rails were considered to have a fixed boundary with the ground, and the displacement of rails were restricted in the vertical and lateral directions, simulating rigid fastening of rails on to the substructure. The railway operations were simulated at a train speed of 160 km/h, as is described in section 2, and the axle load on the wheel-set was varied from the range of 20 – 32.5 tonnes, in discrete numerical analyses. Figure 4 shows the assignment of axle load and definition of train speed on the wheel-set (represented in the figure by downward red arrows and rightward blue arrow, respectively). Each analysis was run with refined time-steps (from about 3E-05 to 3E-02 seconds) and each analysis was completed in 8500 iterations. A convergence criteria of 0.1% was considered for both force and displacement calculations.

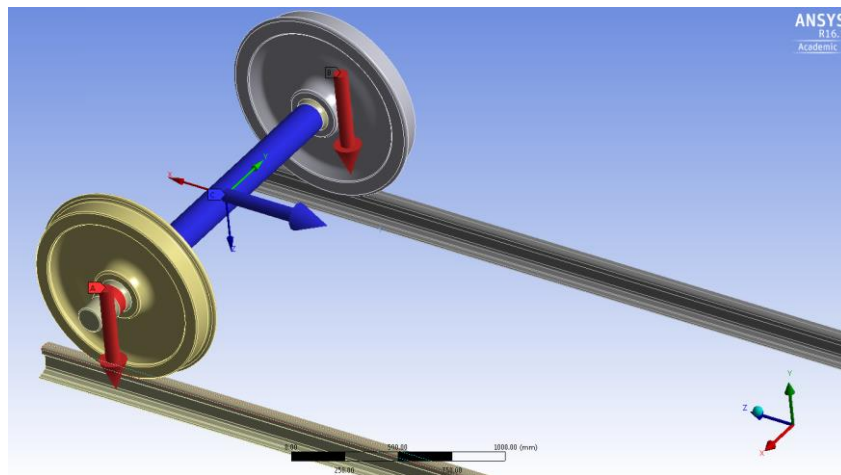


Figure 4. Assignment of axle load and speed of train transit on the wheel-set.

2.4. Results and discussions

Three-dimensional numerical analyses were run, simulating railway operations in the axle load range of 20 – 32.5 tonnes, at a train speed of 160 km/h. The analyses in each loading cases were repeated thrice, and the average results for contact pressure and frictional stresses at the wheel-rail interfaces were noted. Further, variation of the effective frictional coefficient at the wheel-rail interface was plotted, with reference to the variation in the applied axle loads, as shown in figure 5.

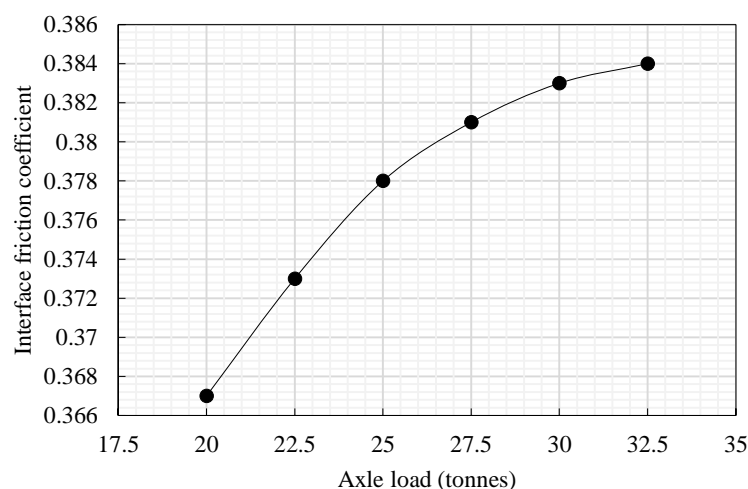


Figure 5. Variation of effective frictional coefficient at wheel-rail interface with increase in axle load.

From the analyses, it could be seen that when train velocities are involved, coefficient of friction at the wheel-rail interface tends to increase with an increase in the applied axle load. The rate at which this coefficient increases has a trend to decline towards higher ranges of axle loads. For the axle load range of 20 – 32.5 tonnes, coefficient of friction at the wheel-rail interfaces were found to be within the range of 0.36 – 0.39, when the simulations were performed at a train speed of 160 km/h.

The trend of graph plotted between effective frictional coefficient and axle loads implies that when trains are designed to be lighter, for gaining higher speeds in railway operations, the traction available at the rail-wheel contact would be highly dependent on the axle load being carried. At high speeds of operation, wheels of the train tend to lift-off from the rails [3], effectively reducing the available traction. Results from this study show that this loss of traction would be augmented further, if lower axle loads are carried by the trains at high speeds. This would cause operational hazards, when a train needs to apply an emergency brake at high speeds, or cause wheel-spins, when high motive power is fed to the wheels for accelerating the train. It can also be pointed out that in case of heavy freight carriers, operations at high speeds would be associated with high coefficients of friction, which could result in damaging of rails due to rolling contact fatigue, and cause rapid wearing in the interacting surfaces of wheels and rails.

3. Conclusions

Three-dimensional numerical simulation of railway operations were carried out in this study for quantifying the variations in the effective frictional coefficient available at the wheel-rail interfaces with changes in the train axle loads. Simulations were run at a train speed of 160 km/h, under an axle load range of 20 – 32.5 tonnes. The observations from the study are summarized as below:

- The effective frictional coefficient at the steel-steel interface of wheel-rail contact was found to be within the range of 0.36 to 0.39, for the applied axle load range from 20 to 32.5 tonnes, at a train speed of 160 km/h.
- Coefficient of interface friction at the wheel-rail contact had a trend to increase with an increase in the applied axle load.
- When train velocities were involved, coefficient of friction was found to be a dynamic parameter, contrary to the case of static loading, where a constant value of frictional coefficient is observed across the loading range.
- The rate of increase in the net frictional coefficient was found to decline towards higher ranges of axle loads.
- Higher coefficients of friction were associated with freight carriers operating at high speeds, which would result in rapid wearing out of wheels and rails and cause deformations in rails due to rolling contact fatigue.
- Operation of high speed trains with lighter axle loads would result in loss of traction and cause wheel-slips, due to the reduced frictional grip at the wheel-rail interfaces owing to the reduction in the effective frictional coefficient.
- Application of friction modifiers shall be decisively considered for maintaining the optimum friction at the wheel-track interfaces, by keeping the effective frictional coefficient at the contact interface around a value of 0.35.
- A wide variety of friction modifiers and friction enhancers are available in the market today, and the choice of specific coating material will be highly dependent on the nature of railway operations and track conditions.
- In case of high-friction contacts, lubrications in the boundary regime, mixed lubrication or hydrodynamic lubrication are applied on the basis of Stribeck curve, adopting the optimum friction coefficients for avoiding rolling contact fatigue and high rates of wear due to plastic deformations [4].

- When there is less frictional grip, as in case of high speed railway operations, a coating of top-of-rail positive friction enhancer may become necessary, for increasing the adhesion characteristics and achieving positive creep.

This study emphasizes the importance of optimizing the friction at the wheel-rail interfaces using engineered friction modifiers. The choice of specific friction modifiers would be highly dependent on the profile of the wheels and rails, and also on the characteristics of railway loading, including the frequency and intensity of the train axle loads.

References

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