Variation of effective frictional coefficient at wheel-rail contact interfaces during high speed railway operations

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Abstract. Numerical simulations were performed for the analysis of wheel-rail interactions in high speed railway networks, and the variation of effective frictional coefficient at the wheel-rail interface during high speed train operations was quantified, with respect to the increase in speeds of trains. The analyses were performed for railway operations ranging from speeds of 160 to 200 km/h, which are the maximum speeds recommended by Indian Railways for safe operation of trains in the broad gauge railway tracks in India. Transient structural analyses were performed using ANSYS, and it was observed that the interface frictional coefficients at wheel-rail interface had a trend to decrease with an increase in the speed of train. This reduction in the coefficient of friction at wheel-rail interface would contribute to a loss of traction due to reduced grip, resulting in locomotive wheel-slips, wastage of motive power and reduced braking efficiency of train wheels on rails during high speed railway operations. Electronic wheel-spin detectors shall be used to control and alter the power supplied by high speed locomotives to train wheels, for maintaining sufficient traction on the rails. Modification of rail and wheel surfaces using friction modifiers will help in maintaining the frictional grip necessary for maintaining safety in railway operations at the targeted maximum speeds of train transit.

1. Introduction
High speed railway networks in India are in their primary stages and much research is in progress for implementation of the network with high safety and reliability. High speed railways contribute to the economic and infrastructural development of a nation. The commuters are endowed with much lesser travel times, reduced use of energy per passenger kilometre and improved safety for the passengers [1]. Operation of trains in high speed railway networks have significant differences from conventional passenger railway operations, from the very speed of operation to the profiles of rails and components of the train. The efficient acceleration and braking of trains are highly dependent on the maintenance of optimum coefficient of friction at the wheel-rail interfaces during high speed train operations [2]. These dynamic responses of the railway vehicle can be controlled by optimizing the sections of wheel-rail profiles and the conditions of contact adhesion [3]. Estimation of the frictional coefficients at wheel-rail interfaces are generally done by performing studies in laboratory rigs or using hand-held field-scale tribometers, which are subject to errors due to scaling factors and difficulties in maintaining the surface roughness [4]. However, full-scale studies can overcome most of these difficulties, but are highly limited by economical constraints and testing space constrictons. Numerical modelling of full-scale railway operations can hence prove to be a reliable method in estimating the friction coefficients.
2. Numerical model for Indian Railways

3-D numerical models were developed for simulation of train operations in Indian Railways, with IRS-52 rail sections laid at broad gauge spacing and wheel-set dimensions as specified by Research Designs & Standards Organisation, under the Ministry of Railways, India [5]. The geometric models were developed in software SOLIDWORKS, and the model was further imported into software ANSYS, for performing the finite element model analyses. Structural steel was assigned as the component material for wheel-set and rails, with the material specifications assigned in accordance with the structural steel adopted by Indian Railways, for field operation of trains. For simplifying the model analysis, rails were considered to be rigid and wheel-set was modelled to be deformable, which combines the advantages of reducing the computational demands imposed by fine meshing of lengthy railway track sections, while simultaneously facilitating the estimation of deformable contact interactions in wheel-rail interfaces during high speed railway operations.

2.1. Model meshing

A solid body mesh size of 27 mm (for wheel-set) and a very fine contact meshing of 1 mm was adopted in the model, based on the model validation studies previously performed by the authors on similar sections of Indian Railway wheel-rail models. Figure 1 shows the model meshing with ultra-fine mesh definition at the wheel-rail interface, which can effectively capture the contact interactions with utmost fidelity.

![Figure 1. Model meshing with 27 mm size for the body of wheel-set and ultra-fine mesh size of 1 mm for the wheel-rail contact interface.](image)

2.2. Wheel-rail contact definition

Asymmetric pair-based contact was defined in the wheel-rail interface, assigning CONTA174 contact elements in the wheel surfaces and TARGE170 target elements in the railhead surfaces (considering deformable wheels to be running over rigid rail sections), as shown in figure 2. The contact solver was based on Augmented Lagrange formulation, with the stiffness set to be updated during each iteration in the analysis. The variations in coefficient of kinetic friction at the steel-steel interface of wheel-rail contact was further set to be monitored at each time step, with reference to the changes in speeds of train operations. Maintaining the optimum frictional coefficient at wheel-rail interface is crucial, since larger deviations of frictional grip from optimal conditions would result in substantial loss of motive power and traction.
Figure 2. Assignment of CONTA174 elements on wheels and TARGE170 elements on rails.

2.3. Loads and boundary conditions

A Fixed boundary conditions were considered beneath the rails and the train speeds from 160 to 200 km/h were simulated in this study, which are the maximum speeds recommended by Indian Railways for train operations in broad gauge railway tracks. An axle load of 32.5 tonnes was defined over the wheel-set, to consider the potential loading conditions in the dedicated freight carriageways. Figure 3 shows the assignment of loading conditions, with the downward arrow showing the direction of axle load and the forward arrow showing the direction of train movement.

Figure 3. Right-side view of the model showing assigned direction of axle load (down-arrow) and direction of train travel (right-arrow).
2.4. Numerical simulation results and discussions

From the high speed railway simulations, it was noted that there was a reduction in the effective coefficient of friction at the wheel-rail interface with increase in the speed of train operations, as shown in figure 4. The frictional stresses at the contact interface were found to vary from 37–39% of the contact stresses at a given instant of time, for the range of train speeds from 160–200 km/h. The decline in coefficient of friction towards higher spectrum of train speeds implies that the rate of increase in frictional stresses at greater train speeds would be slightly lower than the rate of increase in the contact stresses.

However, this case of rolling friction has a significant distinction from surfaces in sliding friction, the theory governing which explains that the coefficient of kinetic friction is independent of the sliding velocity (Coulomb’s law of friction).

![Figure 4](image_url)

**Figure 4.** Reduction in coefficient of wheel-rail interface friction with increase in speed of train.

The observed reduction in coefficient of friction with increase in speed of the train is in agreement with the literature by Popovici [6], which explains that the coefficient of friction reduces due to lift-off of wheels by building up of pressure in the interfacial layer, during higher speeds of train operation. This reduction in the interface frictional coefficient should be considered during design and implementation of high speed railway networks, so that necessary traction can be maintained for safe railway operations. A reduction in the effective frictional coefficient would imply a loss of traction due to reduced grip, which will contribute to locomotive wheel-slips, wastage of motive power and reduced braking efficiency of train wheels on rails. From the previous works of the authors, it was also noted that the net frictional stresses had an increase with the increase in speeds of trains, in spite of this observed reduction in the coefficient of friction.

3. Conclusions

Numerical simulations of train operations in Indian Railways were performed on finite element models, developed with the specifications of field-scale railway operations. The variation of effective frictional coefficients at the wheel-rail interface were quantified with reference to the increase in speeds of train operation, and the following conclusions were drawn from the study:

- The coefficient of friction at the wheel-rail contact had a trend to decrease with an increase in the speed of train, which was found to be in close agreement with the previous studies
conducted by researchers, explaining that the wheels tend to lift-off during high speed train operations.

- Frictional stresses at the wheel-rail contact interface were found to vary from 37–39% of the contact stresses at a given instant of time, for the range of train speeds from 160–200 km/h.
- The decline in coefficient of friction towards higher spectrum of train speeds implies that the rate of increase in frictional stresses at greater train speeds would be slightly lower than the rate of increase in the contact stresses.
- The reduction in frictional coefficient, in effect, would contribute to a decrease in the frictional grip of the train on rails during high speed train transit.
- The efficient acceleration and braking of trains at high speeds will mandate the use of electronic wheel-spin detectors in locomotives, modifications in existing wheel-rail sections and use of surface friction modifiers on rails, to help maintain the effective traction necessary for safe train operations at blazingly fast speeds.

The design of train components and railway lines for high speed railway networks should integrate the structural capacity to cater for high frictional stresses, with the ability to maintain sufficient frictional grip at the wheel-rail interfaces during high speed railway operations.

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