Sindh Univ. Res. Jour. (Sci. Ser.) Vol. 45 (2) 373-378 (2013)

SINDH UNIVERSITY RESEARCH JOURNAL (SCIENCE SERIES)

Anti-Slip Traction Control of Railway Vehicle Based on Estimated Wheel-Rail Contact Condition

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Received 08th January 2013 and Revised 11th January 2013

Abstract: In railway traction system adhesion is an important factor to accelerate the vehicles quickly. If applied tractive effort is greater than allowed by the adhesion level at the wheel-rail interface then wheel slip occurs. Wheel slip is an undesirable phenomenon which reduces the life of mechanical parts thus increasing the overall maintenance cost. Several techniques have been proposed to prevent the wheel-slip in ever-changing weather and environmental conditions. But the available measures are not effective to eliminate the problem completely. This paper presents a novel idea to develop an intelligent mechanism to tackle the problem of wheel slip. The proposed method first indirectly identifies the available adhesion level by analysing the changes in wheelset dynamics with respect to changes in contact condition. The estimated adhesion information is then used to optimize the traction forces in order to avoid slip. The efficacy of the proposed solution is demonstrated with the help of simulation results.

Keywords: Traction control, wheel slip and wheel-rail adhesion

1. INTRODUCTION

Due to rapid advancements in railway technology the railway transport is becoming more reliable public transport all over the world. But still in some parts of the world, where changes in weather conditions are rapid and highly unpredictable, the punctuality and safety of railway transport is still a critical issue. To minimize the disruptions in time tables it is absolutely necessary for the train drivers (or traction control system in driverless trains) to accelerate the vehicle as quickly as possible and also apply the brakes in minimum possible distance. This is only possible when the information about the adhesion level is readily available to the traction control system. The improved knowledge of the contact conditions will help to prevent the occurrence of wheel slip/slide of traction and braking systems on slippery tracks (Johnson, 1987).

Several techniques have been proposed to improve the performance of railway vehicles under severe weather conditions which mostly are reactive in nature (i.e. react only when the wheel-slip is detected) (Ohishi *et al.*, 2006, Knudsen *et al.*, 1994, Davies, 1939). Those techniques rely on the calculation of the slip ratio (difference between vehicle speed and wheels' rotational speed) and react only if the slip ratio exceeds certain threshold value (Yu *et al.*, Arias-Cuevas and Li). Those controllers require accurate measurement of the slip and are difficult to guarantee an optimal performance (Iwnicki, 2006).

Attempts have been made to measure the adhesion level available between wheel and rail but the measured data is not considered reliable due to the presence of several noises generated from various mechanical parts (Johnson, 1987).

Since it is almost impossible to measure the adhesion level directly a number of ideas have been proposed to detect the running condition of the wheel-rail interface indirectly that use vehicle mounted low cost inertial sensors and advanced processing, e.g. an inverse modelling approach for the estimation of creep forces (Xia *et al.*, 2007); and a model based estimation (Ward, Charles *et al.*, 2008).

This paper presents an indirect technique to identify the available adhesion level at the wheel-rail interface. This work is an extension of an ongoing research and is fundamentally different from (Johnson, 1987, Hussain, 2010, Hussain, 2009, Wickens, 2003, Goodall, 1999) in number of ways. Previously only adhesion identification scheme is presented, whereas, in this paper a mechanism is designed to utilize the adhesion information and adjust the tractive effort accordingly. The adhesion identification scheme consists of bank of Kalman filters to estimate the railway vehicle dynamics in different weather and environmental conditions. The data obtained from Kalman filters is then processed further and analyzed by detection system to identify the adhesion level from the dynamic variations of the vehicle. The estimated adhesion information is then provided to traction control system to adjust the throttle accordingly.

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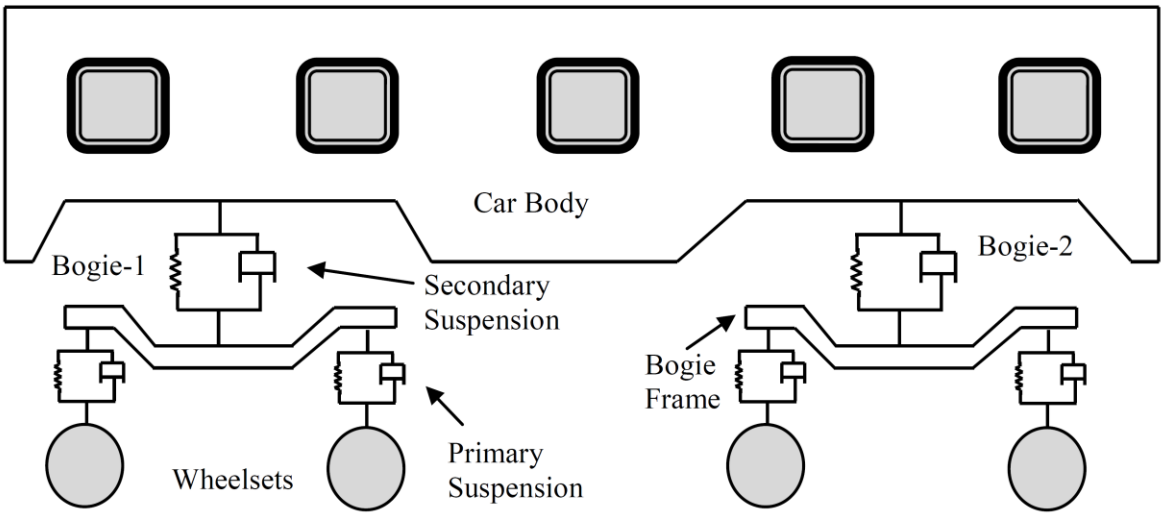


Fig.-1: Bogied Vehicle Configuration

2. MODELLING OF SYSTEM DYNAMICS

There are several different mechanical configurations of railway vehicles in use, among which bogied vehicle configuration, shown in **(Fig.1),** is the most commonly used. Therefore in this paper the study is carried out using this configuration. The mathematical model of a single bogie is used during the simulations to demonstrate the potential of the idea presented here.

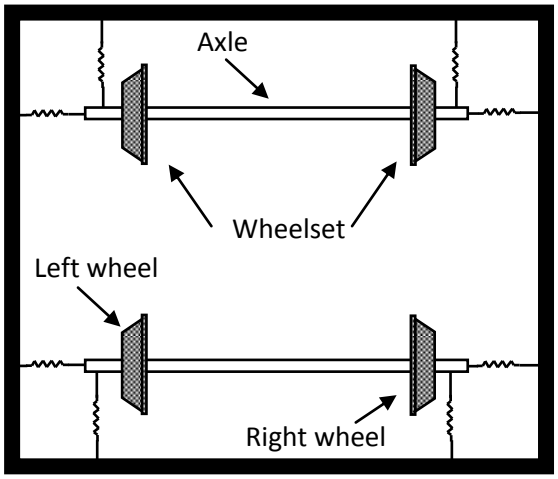


Fig.2: Wheelsets in a Bogie Frame

Fig.2 shows the arrangement of a single bogie. Each bogie consists of two wheelsets. Each wheelset consists of two wheels (left and right side wheels) and are connected rigidly via a common axle (known as the solid-axle wheelset) in a way that the two wheels have to rotate at the same speed. The wheelset are connected to bogie via suspension elements. The purpose of the suspension elements is to isolate the passenger car from the vertical displacement induced by irregularities in railway track. Along with ride comfort, the suspension also serves to improve the stability of the railway wheelset which when unconstrained produces sustained oscillations (Brickle, 1986).

2.1 Dynamic Equations

Railway wheelset consists of two wheels connected on an axle rigidly. Each wheel on the wheelset has a coned tread with a flange on inside as shown in **(Fig.3).**

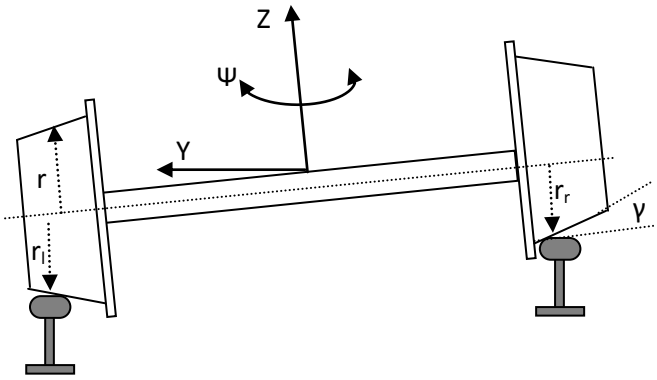


Fig. 3: Railway Wheelsets

In each bogie one of the wheelsets is derived by motor (usually installed on right side of the axle). If T_t is the torque produced by the traction motor then the rotational dynamics of the wheelset are given as:

$$I_R\dot{\omega}_R = T_t - T_k - T_R \quad (1)$$

$$I_L\dot{\omega}_L = T_k - T_L \quad (2)$$

$$\dot{\theta}_k = \omega_R - \omega_L \quad (3)$$

where, I_R is moment of inertia of right wheel, ω_R is angular velocity of right wheel, T_k is torsional torque due to axle stiffness k, T_R is the tractive torque of right wheel, I_L is moment of inertia of left wheel, ω_L is angular velocity of left wheel and θ_k is torsional angle of the axle. T_R and T_L in above equations can be represented in several ways, however, the most

frequently used representation is using linearized Kalker coefficients (Iwnicki, 2003).

$$T_R = r_o f_{11} \lambda_{xR} \quad (4)$$

$$T_L = r_o f_{11} \lambda_{xL} \quad (5)$$

where, r_o is radius of the wheel, f_{11} is linearized Kalker coefficient and represent the amount of adhesion available at wheel-rail contact and λ_{xR} and λ_{xR} represent slip (commonly known as creep) generated at right and left wheel respectively and are defined as the relative speed of the vehicle (v) with respect to track.

$$\lambda_{xR} = \frac{r_o \omega_R - v}{v} \quad (6)$$

$$\lambda_{xL} = \frac{r_o \omega_L - v}{v} \quad (7)$$

Replacing T_R and T_L in equation (1) and (2) yield following wheelset model.

$$\begin{bmatrix} \dot{\omega}_R \\ \dot{\omega}_L \\ \dot{\theta}_s \end{bmatrix} = \begin{bmatrix} -\frac{r_o^2 f_{11}}{v I_R} & 0 & -\frac{k}{I_R} \\ 0 & -\frac{r_o^2 f_{11}}{v I_L} & \frac{k}{I_L} \\ 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} \omega_R \\ \omega_L \\ \theta_s \end{bmatrix} + \begin{bmatrix} \frac{1}{I_R} \\ 0 \\ 0 \end{bmatrix} T_t \quad (8)$$

Equation (8) clearly indicates that the dynamics of the wheelset depend on speed of the vehicle and adhesion at wheel-rail interface, if other parameters are constant. The parameters other than speed and adhesion depend upon manufacturer and are constant once the vehicle is manufactured. Therefore, the important parameters that can affect the stability of a running vehicle are its speed and friction level on the tracks. Low friction level can cause the wheel to slip during traction and slide during breaking. A method of estimating adhesion level is already presented by authors in (Hussain, 2010, Hussain *et al.*, 2012a, Hussain *et al.*, 2012b), which uses vehicle mounted inetial sensors (Gyro sensor for yaw rate measurmentt and an acellerometer for lateral acceleration mesurement) to idendity the available adhesion level. In this paper this model is used to provide the adhesion information to traction control system which in turn adjusts the tractive effort accordingly to avoid wheel slip.

3. RESULTS AND DISCUSSIONS

A simulink model from equation (8) is developed to demonstrate the potential of the idea. Figure-4 shows the effect of slip on the speed of the wheel and vehicle. Adhesion level during the first five seconds of the simulation is kept high (i.e. 40%). After five seconds of simulation adhesion level drops down to 5%. When the adhesion level is high, all the applied traction is used in accelerating the vehicle. During the simulation when adhesion is high, the speed of the vehicle varies in equal proportion with the speed of wheels. Whereas, when the adhesion level is low, speed of the wheels increases abruptly causing the wheels to slip, which if not controlled properly, may cause damage to track as well as rolling stock. It is also waste of tractive effort which reduces the fuel efficiency. **(Fig.5)** shows the block diagram of the proposed idea.

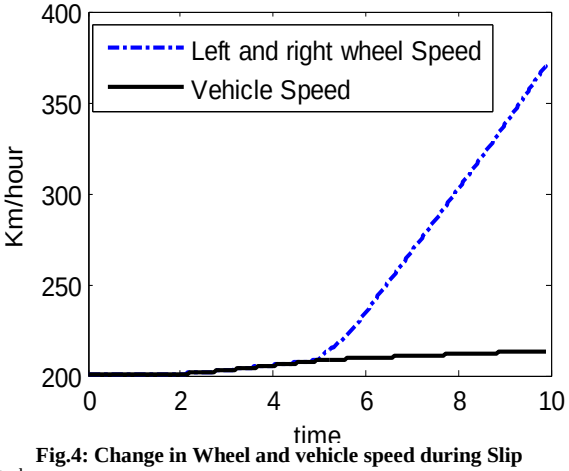


Fig.4: Change in Wheel and vehicle speed during Slip

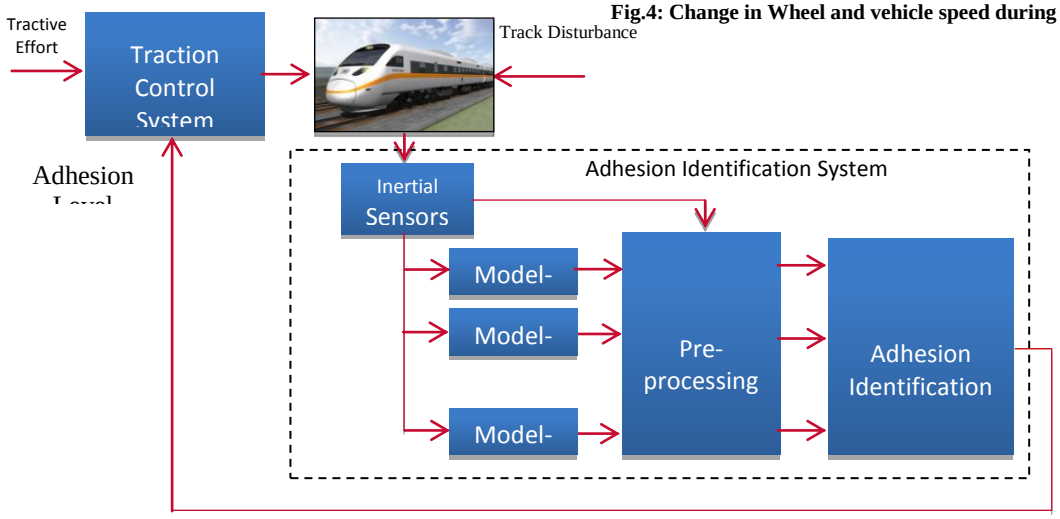


Fig.5: Proposed Traction Control System

(Fig. 6) shows how the traction is varied during the simulation. During the first half of the simulation torsional torque varies smoothly with applied tractive effort. Hence driving the left wheel in similar fashion as the right wheel is driven. When the adhesion level drops down to 5% torsional vibrations are produced in the axle because of the wheel slip. These vibrations are induced into passenger car and affect the ride comfort badly.

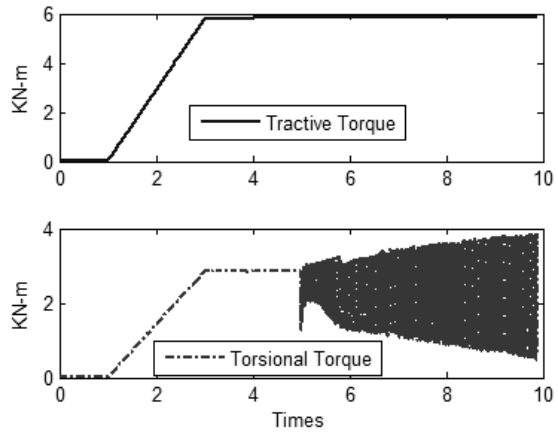


Fig.6: Tractive and Torsional Torques

The adhesion identification system identifies the adhesion level by exploiting the wheelset dynamics. It uses multiple model based technique to estimate the wheelset dynamics in different adhesion conditions. The variations in the wheelset dynamics are studied thoroughly and a technique is developed to extract the adhesion information from the estimated data. The estimated adhesion information is then provided to traction control system to adjust the tractive effort according to equation (9) to avoid wheel slip. The equation (9) shows the maximum tractive torque that can be applied to accelerate the vehicle.

$$T_t = \mu M_v g r \qquad (9)$$

where μ is adhesion coefficient, g is the gravitational force and M_v is mass of the vehicle.

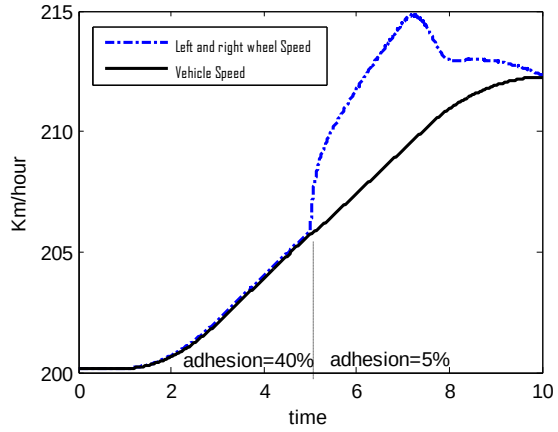


Fig. 7: Tractive and Torsional Torques

(Fig.7) shows when traction control system is used to control the tractive torque. Adhesion level is again switched from high to low after 5 seconds of the simulation. After 5 seconds when the slip occurs the traction control system reduces the tractive torque as shown in **(Fig. 8).** After the reduction of tractive torque vehicle take couple of seconds to adjust and come back to normal operation.

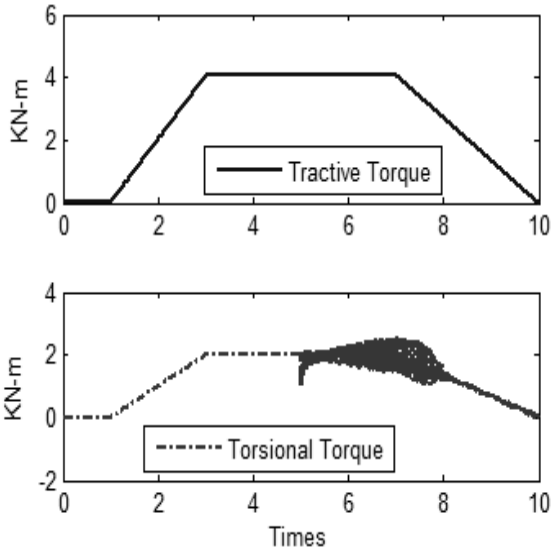


Fig. 8: Tractive and Torsional Torques

4. CONCLUSION

This paper focuses on a critical issue faced by high speed commuter trains around the world. Commuter trains require to accelerate quickly and in doing so, if adhesion level is not sufficient wheel slip occurs. Wheel slip can be avoided if the adhesion information is accurately provided to the traction control system. It is not yet possible to measure the adhesion level because of its dependency on various factors including weather and environmental conditions. Therefore in this paper a traction control system is developed which uses the estimated adhesion level to adjust the applied tractive effort to avoid slip. The efficacy of proposed system is evident from the results resented. Further work can be carried out to improve the recovery time which in this case is more than two seconds. Once the simulation results are satisfactory idea can be put into practice successfully.

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