Alonso, A., Guiral, A., Baeza, L. and Iwnicki, S.

Wheel–rail contact: experimental study of the creep forces–creepage relationships

Original Citation

Alonso, A., Guiral, A., Baeza, L. and Iwnicki, S. (2014) Wheel–rail contact: experimental study of the creep forces–creepage relationships. Vehicle System Dynamics, 52 (S1). pp. 469-487. ISSN 0042-3114

WHEEL-RAIL CONTACT: EXPERIMENTAL STUDY ON THE CREEP FORCES VS. CREEPAGES RELATIONSHIPS

A. Alonso*1), A. Guiral1), L. Baeza2), S.Iwnicki3)
1) CEIT, San Sebastián, Guipúzcoa, Spain;
2) Universidad Politécnica de Valencia, Spain;
3) University of Huddersfield, U.K;

Abstract

The wheel-rail contact problem plays an important role in the simulation methods used to solve railway dynamics problems. Therefore, many different mathematical models have been developed in order to calculate the wheel-rail contact forces. However, most of them tackle this problem from a purely theoretical point of view and need to be experimentally validated. This could also reveal the influence of certain parameters not taken into account in the mathematical developments. This paper presents the most important steps followed in building a scaled test-bench to experimentally characterize the wheel-rail contact problem. The results of the longitudinal contact force as a function of the longitudinal creepage are obtained and the divergences with respect to Kalker's Simplified Theory are analyzed. The influence of the lateral creepage, the angular velocity and some contaminants such as cutting fluid or high positive friction modifier is also discussed.

1. INTRODUCTION

The accuracy obtained when solving most of the Railway Dynamics problems depends greatly on the modeling of the wheel-rail contact. For this reason, during the last decades several research projects have been carried out in order to develop precise mathematical models that allow obtaining the forces transmitted through the contact area. Among these pieces of work, the ones of Kalker [1], Polach [2], Chollet [3] and Alonso [4] can be underlined.

A fact that attracts attention when analyzing the different published papers about the wheel-rail contact problem is that most of them address the problem from a purely theoretical point of view, without including reliable experimental results to validate the theoretical results. The causes of this fact can be found in the high complexity in obtaining experimental measurements. As a result of this lack of experimental results there are large uncertainties in the development of wheel-rail contact models.

The overall objective of this work is to gain experimental knowledge on the wheel-rail contact problem. To this end, a test-bench has been designed and constructed. Subsequently, the test-bench has been used to obtain experimentally the creep forces vs. creepages relationships and its dependence on certain factors such as rotational velocity, surface conditions, etc. Finally, the divergences between the experimental results and the theoretical ones will be analyzed.

2. WHEEL-RAIL TEST-BENCH DEVELOPMENT

In the framework of this project, a test-bench has been designed and developed in order to analyze the contact conditions that are produced in a real railway vehicle and replicate them in a scaled manner. The use of the scaled test-bench is driven by the high cost of reproducing in a laboratory the real conditions, due to the large dimensions, high forces and power required. The scale of the different magnitudes (forces, length, etc.) should be determined in such a way that the conditions obtained in the test-bench are as similar as possible to the existing conditions in a real railway vehicle.

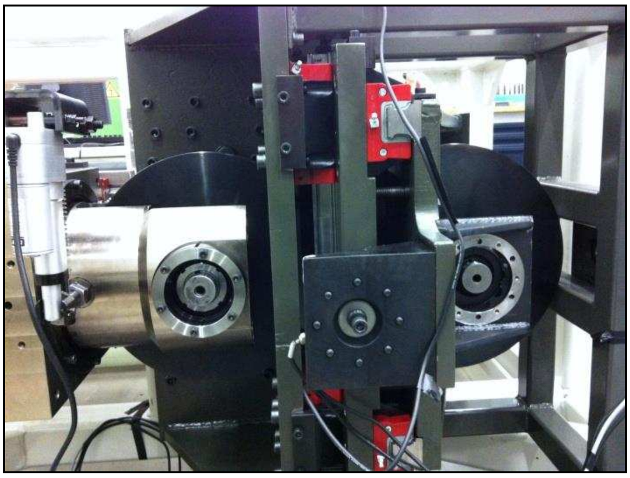


Figure 1. Test-bench.

The scale determination criterion has been done in such a way that the friction coefficient in the test conditions has a similar value to the one existing in the track. As it is known, the friction coefficient between two bodies depends among other factors on normal pressure, tangential tractions, slip velocity, surface conditions, etc. Following this criterion, the following relationships between the different parameters has been obtained

Parameter	**Relation**
Lengths:	$L_R = \Psi \cdot L_S$
Forces:	$N_R = \Psi^2 \cdot N_S$
Angular velocity:	$\Omega_R = \Omega_S / \Psi$

Table 1. *Relation between the real parameter, 'R', and the scaled parameter 'S'.*

The scale parameter determination needs the definition of real conditions of reference. The wheel is supposed to have a radius of 425 mm, the contact takes place on the conic zone, the rail has a curvature of the head profile of 300 mm and the normal load is assumed to be 90 kN. Moreover the following aspects should be considered:

- The power supplied by the engines is critical from the economical perspective. If the power of the motor engine is fixed the maximum achievable theoretical velocity is also fixed.
- The larger the scale parameter, the higher the maximum achievable velocity. Therefore, the larger the scale parameter, the better the friction coefficient dependency on the velocity can be evaluated.
- The contact area decreases by the square of the scale parameter. A large scale parameter value would lead to an excessive reduction of the contact area dimensions moving away from real conditions.

Considering all these aspects, the scale has been given a value of 5. If each motor is able to supply 75 kW, the maximum achievable velocity will be 125 km/h. In order to achieve higher velocities, the motor should be replaced in order to supply greater power.

3. RESULTS

This section presents the experimental results that have been obtained. The aim is to study the influence of the parameters listed below on the wheel-rail contact forces:

- Longitudinal creepage

- Lateral creepage
- Rotational Velocity
- Surface conditions

The results have been compared with the theoretical results given by FastSim [5]. The cleanness of the rollers surfaces is assured by means of the application of isopropyl alcohol, which eliminates possible unwanted substances. Under these clean conditions the friction coefficient value is 0.6.

The procedure followed in order to carry out the experiments is basically divided into three steps: application of the normal load, specification of the angular velocity and introduction of longitudinal relative slip between rollers. The latter can be introduced by means of two types of control; break torque control (TC), which is used for the evaluation of small longitudinal creepage values (up to 0.4%) and velocity control, which introduces an angular velocity difference between rollers allowing the evaluation of higher longitudinal creepages (up to 2%).

3.1. Longitudinal creepage

The first set of experiments evaluates the behavior of the longitudinal force as a function of the longitudinal creepage when the lateral creepage and spin creepage are zero. The rollers are compressed with a normal load of 2.1 kN and the rotational velocity is set to 500 rpm.

Figure 1a shows the longitudinal force as a function of the longitudinal creepage. Additionally, theoretical results obtained with FastSim have also been included. The tangential force, which in this case is reduced to the longitudinal force, can be normalized by means of the normal load and the friction coefficient as shown in Figure 1b.

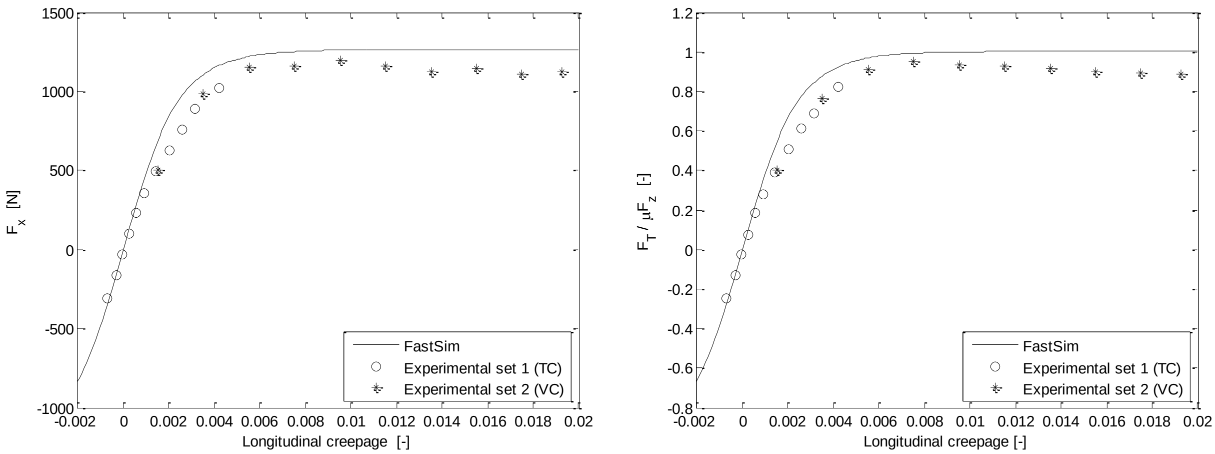


Figure 1. Theoretical-experimental comparison of a)the longitudinal contact force and b) the adimensionalized tangential force vs. longitudinal creepage. $F_z = 2.1$kN, $\Omega = 500$rpm, $\mu = 0.6$

For small longitudinal creepage values the theoretical results are very close to the experimental ones. For higher values, in the non-linear zone, the theoretical estimated force is higher than that experimentally obtained. In the saturation zone, after a maximum force value is reached, a decay is observed. This reduction may be related to the falling of the friction coefficient for high slips; an effect, that is not taken into account in the simplified theory. However, it is worth pointing out, that the falling of the friction coefficient seems to be almost negligible.

3.2. Lateral creepage

The angle of attack between both rollers is directly related to the lateral creepage. In this section, the angle of attack of the left roller will be varied (see Figure 1) in a discrete manner. Nevertheless, the roller on the left is attached to a mechanized piece that has a lineal actuator, which is able to the angle of attack continuously. The design of this piece is complex since the roller rotates in two directions.

Moreover, the desired measurable variation of the lateral creepage is of the order of 0.1 mRad; thus, the piece must be sufficiently robust to avoid deviations of more than 0.01 mRad.

In the following figures the rollers are compressed with a normal load of 2.3 kN and the angular velocity is set to 500 rpm. The friction coefficient between surfaces is μ=0.5. As in the previous section, the longitudinal creepage will be varied by means of break torque and angular velocity control, but now three different angle of attack values will be evaluated: 0.37, 1.66 and 2.36 mRad.

Angle of attack 1: 21 mDeg = 0.37 mRad

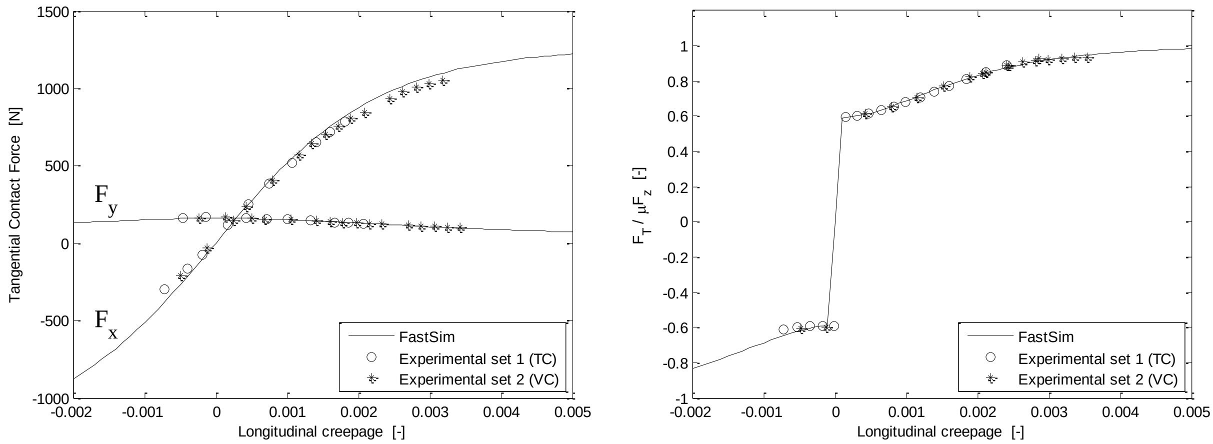


Figure 2. Theoretical-experimental comparison of a)the tangential contact forces and b) the adimensionalized tangential force vs. longitudinal creepage for an angle of attack of 0.37 mRad.

Angle of attack 2: 95 mDeg = 1.66 mRad

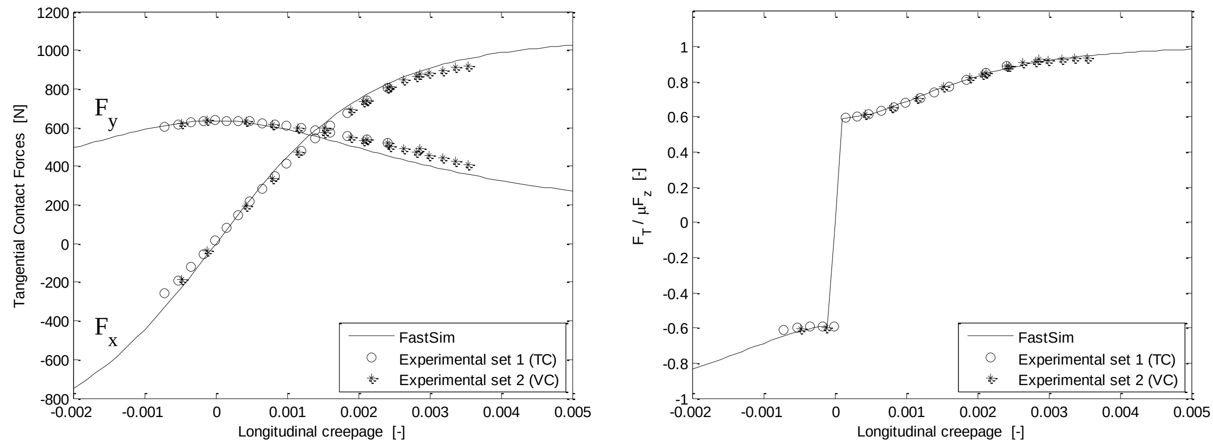


Figure 3. Theoretical-experimental comparison of a)the tangential contact forces and b) the adimensionalized tangential force vs. longitudinal creepage for an angle of attack of 1.66 mRad.

Angle of attack 3: 135 mDeg = 2.36 mRad

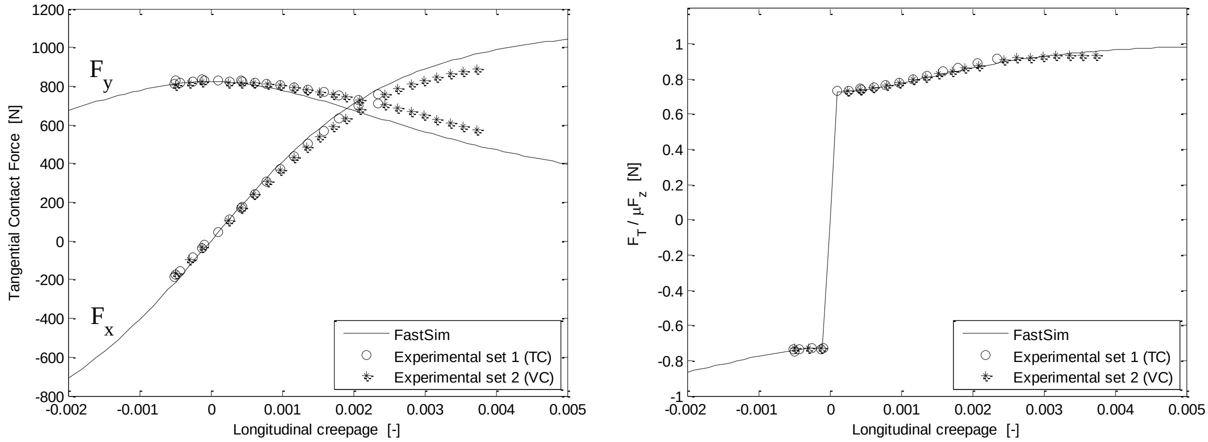


Figure 4. Theoretical-experimental comparison of a)the tangential contact forces and b) the adimensionalized tangential force vs. longitudinal creepage for an angle of attack of 2.36 mRad.

Figure 4, Figure 5 and Figure 7 present the theoretical-experimental comparison of the tangential contact forces and the adimensionalized tangential force as a function of the longitudinal creepage for the discrete values of the angle of attack. For a zero longitudinal creepage the lateral contact force presents its maximum value. The higher is the angle of attack the higher is the lateral force peak value and the discontinuity of the adimensionalized contact force. As the longitudinal creepage increases the longitudinal contact force increases and the lateral force decreases.

In the lineal zone, the experimental results coincide with the theoretical prediction. Nevertheless, as it was pointed out in the previous section, a small divergence is presented as the longitudinal creepage is increased. The divergence between the theoretical and experimental results is presented on both tangential forces – longitudinal and lateral force – and becomes more noticeable as the angle of attack increases.

3.3. Rotational velocity

The tangential contact force depends on the material properties of wheel and rail, the creepages and the friction coefficient between surfaces [6]. The material properties, as well as the creepages, do not depend on the rolling velocity; however, the friction coefficient is thought to vary with the sliding velocity. Thus, as the creep level increases beyond the saturation point the creep force reduces due to the decay in the friction coefficient value. A common assumption made by the wheel-rail contact theories is neglecting the dependency of the friction coefficient on rolling velocity. The entire problem becomes then independent of the rolling velocity. The simplification of the constant friction coefficient could be adopted in the solution of some problems where the wheel/rail slips are small. However, at high slips the falling characteristic of the friction coefficient is believed to play a great role in critical railway dynamics problems such as in simulation of reduced radius curve negotiation, traction torque control on start up, squeal noise, determination of dynamic instability conditions, etc.[7]. Nevertheless, the experimental results for the longitudinal creep force have shown no evidence of an appreciable decrease of the friction coefficient. Therefore, it can be stated that the assumption of the tangential forces independency on the angular velocity is correct not only for small creepages but also for larger values of the relative slip between wheel and rail.

Figure 5 shows the results of the longitudinal contact force when the rollers are compressed with a load of 2.39 kN and a friction coefficient of μ=0.60. Two different angular velocities are tested: 375 and 500 rpm.

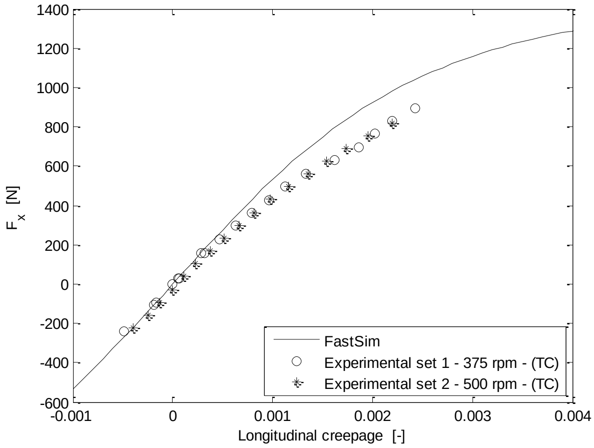


Figure 5. Theoretical-experimental comparison of the longitudinal contact force vs. longitudinal creepage for two different rotational velocities: 375 rpm and 500 rpm. F_z = 2.39kN,

No difference between both experimental sets is appreciated. It can be concluded that, as stated by the theoretical models, for small slip values the problem is velocity independent. Nevertheless, experimental results for higher values of the longitudinal creepage should be obtained.

3.4. Surface conditions

Wheel and rail surfaces condition plays an important role in the wheel-rail contact problem. Typical contaminants that can interfere at the wheel-rail contact interface are water, sand, leaves, grease, oil or friction modifiers among others. All these factors influence the friction coefficient and, therefore, the creep forces values. This section presents some initial results of the tangential contact forces under the influence of interface materials such as friction modifiers and oil.

Cutting fluid or lubricant

The surfaces conditions were changed by adding cutting fluid to the rollers surfaces. Two different friction coefficient values were experimented: μ=0.15 and μ=0.45. A thin film of lubricant was spread onto the profiles in the beginning of the experiments, which was enough to maintain constant the friction value during the whole experiment sets extraction. In both cases the rollers were compressed with a normal load of 2.3 kN and the angular velocity was set to 500 rpm.

Figure 6 shows the theoretical-experimental comparison of the tangential contact force for the lowest friction coefficient value: μ=0.15.

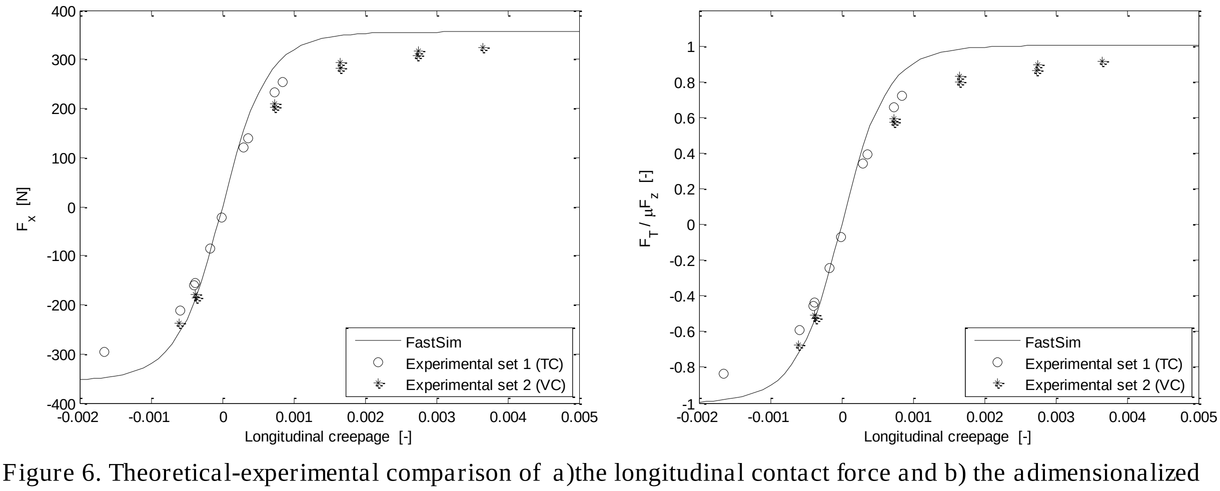


Figure 6. Theoretical-experimental comparison of a)the longitudinal contact force and b) the adimensionalized tangential force vs. longitudinal creepage. F_z = 2.37 kN, Ω=500rpm, μ=0.15

As shown, the behaviour of the longitudinal contact force is similar to that of dry conditions. The theoretical results are in accordance with the experimental results in the lineal zone, but show small differences in the non-lineal zone. The maximum longitudinal force reached value is 323.4 N.

The same experiment is carried out with a higher friction value (μ=0.45). This time, however, higher slip values are tested.

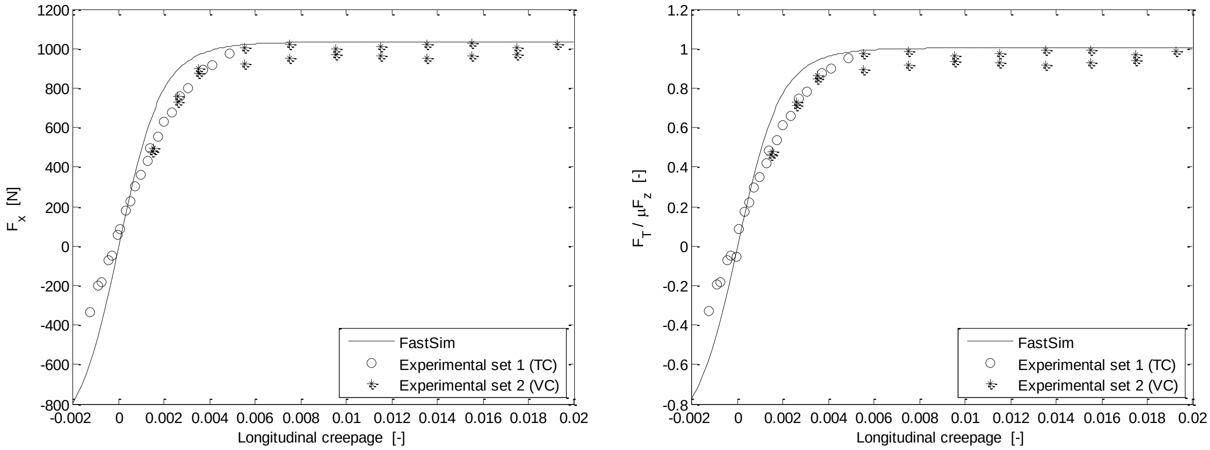


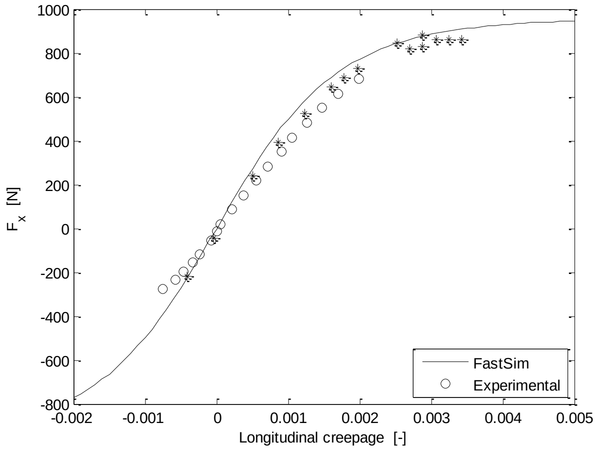
Figure 7. Theoretical-experimental comparison of a)the longitudinal contact force and b) the adimensionalized tangential force vs. longitudinal creepage. F_z = 2.29kN, Ω=500rpm, μ=0.45

As expected, the behaviour of the longitudinal contact force does not change. However, it is worth pointing out that no decay of the contact force is observed for high slips when using lubricant.

High positive friction modifier (HPF)

The use of friction modifiers is rapidly increasing due to their advantages when dealing with problems such as squeal noise mitigation, damaging lateral forces reduction, wear, corrugation or rolling contact fatigue reduction [8]. These products control the friction level at the wheel-rail interface providing an intermediate friction coefficient of 0.35. Moreover, they increase the friction coefficient value with increasing creepage values mitigating the effects of the negative creep slope, which is said to be responsible for the stick-slip mechanism generation leading to the possible occurrence of the previous mentioned problems.

In order to evaluate the wheel-rail contact forces when HPFs are used a water-based friction modifier known as KELSAN® was used. It was spread onto one of the rollers and transferred to the other making them roll slowly. The water was evaporated forming a dry thin film on the rollers surfaces.



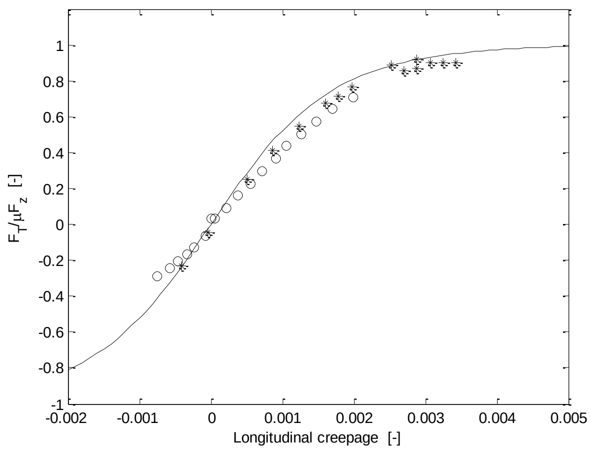


Figure 8. Theoretical-experimental comparison of a)the longitudinal contact force and b) the adimensionalized tangential force vs. longitudinal creepage. F_z = 2.39 kN, Ω=500rpm, μ=0.40

Figure 8 shows the longitudinal and non-dimensional tangential contact force as a function of the longitudinal creepage when a normal load of 2.39 kN is applied and the angular velocity is set to 500 rpm. When applying the HPF, the friction coefficient reduces from 0.60 (dry conditions) to 0.40, which is in the range specified by the manufacturer [8]. In order to evaluate the positive friction characteristic experimental results at higher slip level should be carried out.

4. CONCLUSIONS AND FUTURE RESEARCH WORK

The importance of the wheel-rail contact problem in the dynamic behaviour of railway vehicles has led to the publications of different mathematical developments that tackle this problem mainly from a purely theoretical point of view. As a result, there are large uncertainties concerning the experimental relationships between forces and slips and regarding the influence of some parameters that are not taken into account in the mathematical models. Therefore, the overall objective of the work shown in this paper is to characterize experimentally the wheel-rail contact problem. For that purpose a test-bench was built, and the technical specifications and conceptual design presented.

The results presented provide a theoretical experimental comparison of the tangential contact forces as a function of the longitudinal creepage. The comparison with Kalker’s Simplified Theory theoretical results has shown good agreement for small longitudinal creepages values. In the non-linear zone, however, the theoretical results give an overestimation of the contact force. In the saturation zone, the experimental results show a decay of the contact force that is not taken into account by the theory.

The influence of the angle of attack between both rollers has been also evaluated. Three different curves have been obtained. The results are equivalent to those obtained for the longitudinal creepage. In the lineal zone, the experimental results coincide with the theoretical prediction. Nevertheless, as the slip is increased both the longitudinal and tangential force present some differences with respect to the theoretical results.

Wheel and rail surfaces condition plays an important role in the wheel-rail contact problem. The surface conditions have been modified by adding cutting oil and HPF. Some initial results have been shown, in which it was appreciated that the friction coefficient remained constant when using cutting oil. However, wheel-rail contact forces should be tested under more contaminants such as sand or water, which are very common substances.

5. ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the Spanish Ministry of Economy and Competitiveness (project TRA2010-17671) and to the Government of the Basque Autonomous Community of Spain for their financial support.

6. REFERENCES

[1] J. J. Kalker, Three-Dimensional Elastic Bodies in Rolling Contact, 1st ed. Dordrecht: Kluwer Academic Publisher, 1990, p. 314.

[2] O. Polach, "A Fast Wheel-Rail Forces Calculation Computer Code," Vehicle System Dynamics, vol. 33, pp. 728–739, 1999.

[3] J. B. Ayasse and H. Chollet, "Determination of the Wheel–Rail Contact Patch in Semi-Hertzian Conditions," Vehicle System Dynamics, vol. 43, no. 3, pp. 161–172, 2005.

[4] A. Alonso, "Nuevos Desarrollos para la Resolución del Problema de Contacto Rueda-Carril y su Aplicación a Simulaciones Dinámicas," CEIT, 2005.

[5] J. J. Kalker, "A Fast Algorithm for the Simplified Theory of Rolling Contact," Vehicle System Dynamics, vol. 11, pp. 1–13, 1982.

[6] J. J. Kalker, "Rolling Contact Phenomena: Linear Elasticity." Delft.

[7] J. G. Giménez, A. Alonso, and E. Gómez, "Introduction of a friction coefficient dependent on the slip in the FastSim algorithm," Vehicle System Dynamics, vol. 43, no. 4, pp. 233–244, Apr. 2005.

[8] K. T. Corp., "KELTRACK® Trackside™ Top-of-Rail Friction Modifier." [Online]. Available: http://www.lbfoster-railtechnologies.com/Index.asp.