



HAL
open science

From the third body layer modeling to its effect on railway vehicle dynamics

Moncef Toumi, Hugues Chollet, Honoré Yin, Samir Assaf

► **To cite this version:**

Moncef Toumi, Hugues Chollet, Honoré Yin, Samir Assaf. From the third body layer modeling to its effect on railway vehicle dynamics. Dynamics of Vehicles on Roads and Tracks Vol 2, CRC Press, pp.1185-1190, 2018, 9781138035713. 10.1201/9781351057189 . hal-04496598

HAL Id: hal-04496598

<https://hal.science/hal-04496598>

Submitted on 8 Mar 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

From the Third Body Layer modeling to its effect on railway vehicle dynamics

M. Toumi

IRT Railenium, Famars, France

H. Chollet

COSYS/GRETTIA, IFSTTAR, UPE, Champs sur Marne, France

H. Yin

Laboratoire Navier, Ecole des Ponts, IFSTTAR, CNRS, UPE, Champs sur Marne, France

S. Assaf

IRT Railenium, Famars, France

ABSTRACT: Kalker's rolling contact theories allow good estimation of the creep forces only for situation with scrupulously clean surfaces. When wear particles mix with the substances added naturally or artificially, a Third Body Layer (3BL) is formed at the wheel-rail interface. This layer influences the initial slope of the creep force characteristic. A 3D finite element model is developed in this paper to study the wheel-rail rolling contact in the presence of a thin elastic 3BL at the rail surface. The result shows reduction in the initial slope of the creep forces characteristic i.e. Kalker's coefficients. In order to evaluate the effect of the 3BL on railway vehicle dynamics, a reducing factor K is evaluated from the creep curve then applied to the multi-body software VOCO. The study of derailment shows a slight decrease of the peak of Y/Q ratio which remains above Nadal criterion. However, the critical speed of the vehicle is considerably reduced when the factor K is applied.

1 INTRODUCTION

From the first creep force measurement until nowadays, the decrease of the initial slope of the creep force characteristic has always been mainly attributed to surface contamination and to the 3BL. The origin of the 3BL concept, consisting of wear debris and liquid lubricant, dates back to the work of Godet (Godet 1984) carried out in the 70's in which he proposed a general approach of contact between two bodies connecting the friction to the wear mechanism. This concept is different from the mathematical formalism of Reynolds (Reynolds 1886) in which the notion of the third body is limited to a liquid lubricant.

Several works followed (Berthier et al. 2004, Niccolini et al. 2005, Colas et al. 2013), the aim of which is to have a better understanding of the role of this third body and its influence on the friction and the various mechanisms of damage (wear, cracking ...). This understanding is an essential step before introducing such effects into the various numerical models.

In the case of the wheel-rail contact, the interaction between the first two bodies leads, under certain solicitations, to a thin 3BL composed of wear debris detached from the first two bodies. This third "natural" body generally mixes with a third "artificial" body composed of different types of contaminants which may exist on the wheel-rail interface (Hobbs 1967, Pritchard 1980, Pearce et al. 1982) as contaminants due to climatic conditions (dead leaves, water, frost ...), contaminants due to operating conditions (lubricating oil, sand, crushed stone from the track ballast ...) or external pollutants. The study of the third body is a complex task since the interface of the wheel-rail contact is a field of interaction between several phenomena and behaviors of mechanical, physical, chemical and thermal nature. Berthier (Berthier et al. 2004) has shown that the flow of a layer of third body between the wheel and the rail, of thickness ranging from a few to tens micrometers, ensures the accommodation of the sliding between these two bodies. The presence of this layer also provides some protection against surface cracking and thus extends the life of the wheel and the rail.

On the other hand, several measurements of which a synthesis is presented by Hobbs (Hobbs 1967), have shown the important role played by surface contamination on the decrease in the initial slope of the creep curves, essentially in the longitudinal direction. To account for these effects, several models have been developed. Polach (Polach 2005) modeled the decrease of the initial slope in the longitudinal direction by means of two reduction factors k_s and k_a respectively for the adhesion and the sliding zone, introduced in his semi-empirical model. These factors are determined from experimental measurements of the creep curves carried out on several different vehicles under different operating conditions. Vollebregt (Vollebregt 2014) extended in 2014 the complete Kalker theory implemented in CONTACT by introducing a homogeneous and isotropic elastic layer between the wheel and the rail in which auxiliary displacements occur. Based on a similar approach, Meierhofer (Meierhofer et al. 2014) developed, during the same year, a physical model that considers the plastic deformation of the third body. The elasto-plastic behavior is introduced using the rheological model of Hou (Hou et al. 1997). However, Meierhofer's model is limited to line contact.

It is proposed in this paper to study with the 3D finite element model described in (Toumi et al. 2016b), the influence of a 3BL between the wheel and the rail on the creep force characteristic. The result is then applied to railway vehicle dynamics in order to evaluate the effect of 3BL on derailment and the critical speed.

2 NUMERICAL MODEL

The 3D finite element wheel-rail contact model developed in (Toumi et al. 2016b) is extended in this paper to take into account the presence of the 3BL. The wheel profile is a conical S1002 wheel type (S1002 in which the tread is replaced by a cone) and the rail is an UIC60. It is assumed that a thin layer is placed on the rail interface as shown in Figure 1. It is also assumed that this layer is homogeneous, isotropic and deforms only elastically. Kalker (Kalker 1992) presented a phenomenological model in which he made the hypothesis that the 3BL is much more flexible than the first two bodies. A similar hypothesis is adopted in this work. A shear modulus $G=820$ MPa is defined for the 3BL, 100 times lower than that of steel, i.e. 100 times more flexible than the wheel and the rail. It is also assumed that the thickness h of this layer is equal to $125 \mu\text{m}$ (Vollebregt 2014). This choice can be justified by the different measurements of the 3BL. Indeed, these measurements have led to different thicknesses h , which vary according to experimental conditions from about $0.41 \mu\text{m}$ (Bucher et al. 2002) to a value between $150 \mu\text{m}$ and $200 \mu\text{m}$ (Descartes et al. 2005).

Considering that the 3BL is tied on the rail interface, his movements follow that of the rail which moves in the longitudinal direction with the speed V_x . As the wheel and the rail, the 3BL is meshed with 8 nodes hexagonal elements. The total elements number is equal to 247000. This high number leads to high computational cost. Thus, the creep force characteristics will be studied only in the longitudinal direction.

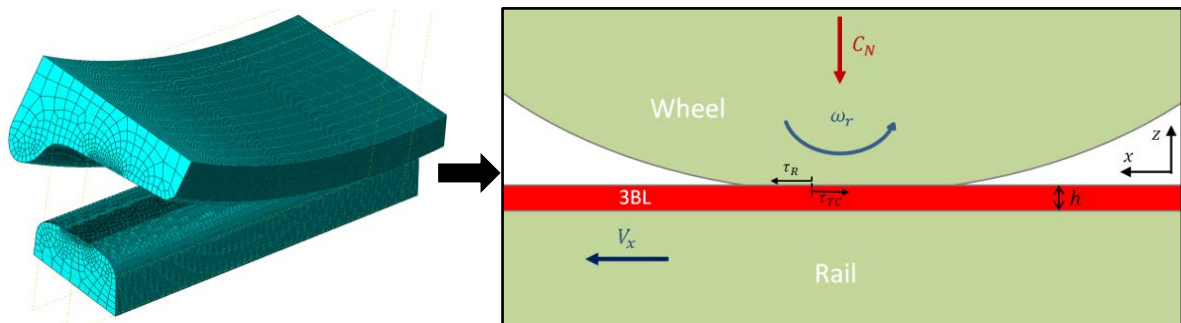


Figure 1. Wheel-rail contact model with 3BL on rail interface

3 RESULTS

3.1 Creep force characteristic

Figure 2 shows the creep force characteristic in the longitudinal direction from the model described in the previous section. Without the presence of the third body, the curve is composed of three different zones: a first micro-creep zone which corresponds to the initial slope of the curve, in general it is in this zone that the Kalker's coefficients are calculated since the wheel and the rail stick completely (condition to satisfy Kalker's linear theory (Kalker 1967)). Then, a second non-linear transition zone which connects the low creepages zone to the high creepages zone, the contact area in this zone is composed of a stick and a sliding zone. Finally, a third macro-creep zone in which the longitudinal force F_x saturates and the two bodies in contact are in total sliding over the entire contact area. With the presence of an elastic 3BL, the initial slope of the creep force characteristic decreases as described by the different measurements which leads to a reduction of the C_{11} Kalker's coefficient. Second, the transition zone becomes larger which leads to a shift of the saturation limit from 3.5 ‰ to about 7.4 ‰. However, according to the result in Figure 2, the 3BL has no effect on the saturation zone of the creep curve and does not lead to "falling friction". These effects on the creep force characteristic due the 3BL are also verified by Vollebregt (Vollebregt 2014) and Meierhofer (Meierhofer et al. 2014).

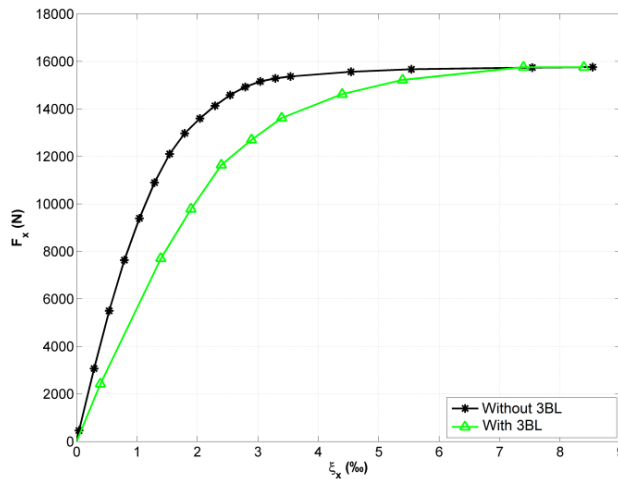


Figure 2. Creep force characteristic in the longitudinal direction in the presence of an elastic 3BL between the wheel and the rail, with thickness $h=125 \mu\text{m}$ and shear modulus $G=820 \text{ MPa}$

By plotting the derivatives of the creep curve and calculating the difference of the initial slope with respect to the linear theory (not represented in Figure 2), it is possible to evaluate the reduction factor in the longitudinal direction due to the addition of an elastic 3BL, which is equal to $K_{11}=0.5$.

It is assumed that the reducing factor identified in the longitudinal direction is also valid in the lateral direction. Thus, we consider that the reduction applies in the same way in the different directions i.e. $K=K_{11}=K_{22}=K_{23}$. In order to study the effect of this 3BL on the railway vehicle dynamics, the factors K are directly applied to Kalker's coefficients C_{ij} in the multibody software VOCCO.

3.2 Effect of 3BL on railway dynamics

3.2.1 Derailment

The risk of derailment is conventionally considered only for the outer wheel (the wheel that tends to derail), in the case of a single saturated contact area on the wheel flange, with loss of contact on the wheel tread. It is by considering the equilibrium of the complete axle that one comes to take into account the contact on the tread of the inner wheel (the second wheel of the axle) possibly unsaturated, and therefore sensitive to Kalker's coefficients C_{ij} .

In reality, as by simulation, the force Y on the outer wheel is obtained as a function of the forces equilibrium over the whole axle, in the presence of spin and longitudinal creepage. Apart from the suspensions towards the bogie, which of course play a role, the role of the inner wheel is important. This other wheel is said to be "pushing" because like any front axle of a conventional bogie in curve, the lateral force tends to push the axle towards the outside of the curve while the force N on the wheel flange of the outer wheel keeps it in a stable state, or not.

As far as the precision of the tangential forces is concerned, it is often not necessary for the outer wheel to have accurate values of tangential forces, since the creepages are very important, so the contact is saturated: Kalker's coefficients are important only in the transitional phases. It is not the same for the inner wheel: the contact is in the wheel tread as studied before with the finite element method, the contact forces are rarely saturated. A reduction of the Kalker's coefficients could have an influence on the final equilibrium of the axle, and thus on the numerical values of Y and Q obtained by calculation.

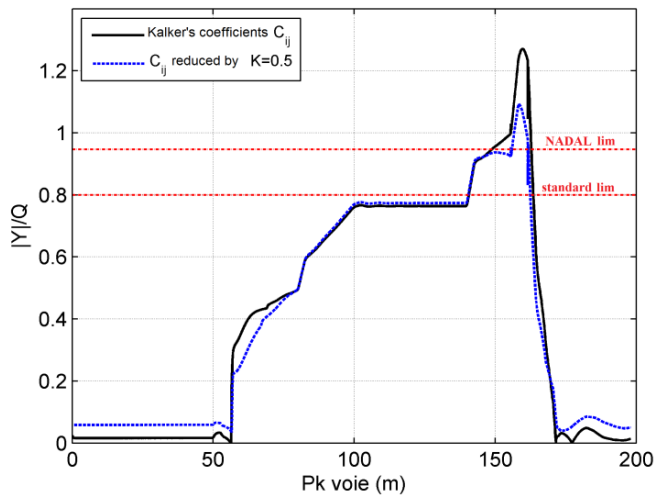


Figure 3. Effect of the reducing factor K on Y/Q ratio, $\mu=0.5$

To study the derailment, the Manchester Benchmark (Iwnicki 1999) adapted to theoretical profiles used in the finite element model was simulated crossing a track curve. The effect of 3BL on derailment is evaluated by comparing the Y/Q ratio obtained on the outer wheel of the front axle in two cases; The coefficients $K=1$ and $K=0.5$ estimated from the finite element model. Figure 3 shows that the ratio Y/Q calculated with the classical Kalker's coefficients ($K=1$) exceeds the Nadal criterion when the train exit the curve after a distance equal to 162 m. When applying $K=0.5$, the peak of the Y/Q ratio decreases from 1.27 to 1.08 but remains above the limit of the Nadal criterion (Nadal 1896) equal to 0.94.

On this particular case, it can be concluded that the reduction of Kalker's coefficients slightly reduces the Y/Q ratio in the delicate zone and reduces the risk of train derailment according to the Nadal criterion.

3.2.2 Critical speed

When the critical speed is needed for the bogie or a full vehicle rather than a single wheelset, the stability analysis is generally conducted numerically. Many dynamicists use the *ramping* method to get rapidly good approximation of the critical speed of a railway vehicle. However, when accurate solution is needed, the bifurcation diagram method is preferred: The main idea is to perform, with the use of the dynamic code, multiple simulations of a train model rolling at various constant initial speeds V over a track presenting some chosen irregularity, then, collect after the establishment of the steady state behavior the final amplitude of the lateral displacement u_y at which the oscillations stabilize.

Figure 4 shows the bifurcation diagram obtained from the simulation of the Manchester Benchmark when applying the reduction factor $K=0.5$ in the multibody software VOCCO. The critical speed decreases when Kalker's coefficients are reduced by K from 280 Km/h to 170 Km/h. In other words, the classical Kalker's coefficients overestimate the critical speed. Alt-

though some teams apply corrections to Kalker's coefficients in their contact algorithms, most dynamistists don't and simply retain the value of $K=1$ (without reduction). This choice is justified by the fact that the contact tangential forces obtained with the classical Kalker's coefficients are naturally higher, therefore the simulations are carried out under the most severe operating conditions (Magel 2014). However, Figure 4 clearly shows the significant impact of the reduction coefficients on the critical speed. Such a high impact can't be neglected and a correction should be applied. Moreover, this correction makes it possible to have a better fit with practice in situations where the hypotheses of Kalker theories are not well respected (Kalker 1992) as when the contact surfaces are contaminated or when the wheel and the rail deform plastically (Toumi et al. 2016a).

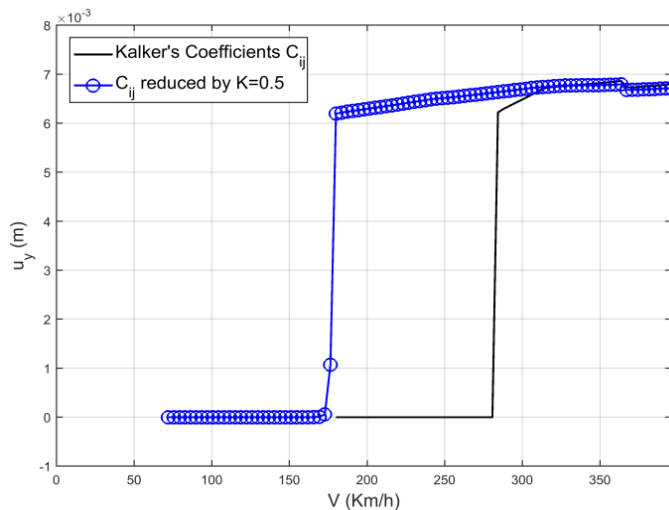


Figure 4. Effect of the reducing factor K on critical speed V_c

4 CONCLUSION

A 3D finite element model that was developed to study the wheel-rail rolling contact is used in this work to investigate to effect of a thin elastic layer of third body layer on the creep force characteristic. A reduction factor is then evaluated from the creep curve and applied to the multi-body software VOCO to study the influence of the Third Body Layer on derailment and the critical speed of a railway vehicle.

It is found from the chosen case study that the Third Body Layer considerably reduces the initial slope of the creep force characteristic in the longitudinal direction and therefore the Kalker's coefficient. Despite the significant reduction applied to Kalker's coefficients ($K=0.5$) the result shows only a slight impact on the derailment of the train. However, this reduction highly reduces the critical speed which means that the actual Kalker's coefficients overestimate this critical.

Although the approach proposed in this paper allows a better study of derailment and a good estimate of the critical speed under more realistic conditions, it remains essential before verifying the effect on the coefficients C_{ij} to further observe the thickness of the 3BL, to measure their real shear modulus and to determine the elastic limit in the contact area which plasticizes, in order to be able to conclude on their impact in simulation of the vehicle stability. It is then necessary to carry out simulations with different wheel-rail couples and different vehicles before proposing the best correlation between these reduction factors.

REFERENCES

Berthier, Y., Descartes, S., Busquet, M., Niccolini, E., Desrayaud, C., Baillet, L., & Baietto-Dubourg, M. C. 2004. The role and effects of the third body in the wheel-rail interaction. *Fatigue Fract. Engng. Mater. Struct.*, vol. 27, pp. 423-436.

- Bucher, F., Knothe, K. & Theiler, A. 2002. Normal and tangential contact problem of surfaces with measured roughness. *Wear*, vol. 253, pp. 204-218.
- Colas, G., Saulot, A., Godeau, C., Michel, Y. & Berthier, Y. 2013. Decrypting third body flows to solve dry lubrication issue – MoS₂ case study under ultra high vacuum. *Wear*, vol. 305, pp. 192-204.
- Descartes, S., Desrayaud, C., Niccolini, E. & Berthier, Y. 2005. Presence and role of the third body in a wheel–rail contact. *Wear*, vol. 258, pp. 1081-1090.
- Godet, M. 1984. The third-body approach : a mechanical view of wear. *Wear*, vol. 100, pp. 437-452.
- Hobbs, A. E. W. 1967. A survey of creep. *British Railways Research Dpt Report note DYN 52*.
- Hou, K., Kalousek, J. & Magel, E. 1997. Rheological model of solid layer in rolling contact. *Wear*, vol. 211, pp. 134-140.
- Iwnicki, S. 1999. The Manchester Benchmark for Rail Vehicle Simulation, *Vehicle System Dynamics*, vol. 31.
- Kalker, J. J. 1992. Modification of the two body contact conditions to account for the third-body. *Tribology Series*, vol. 21, pp. 183-189.
- Kalker, J. J. 1967. On the rolling contact of two elastic bodies in presence of dry friction. *Thesis, Dpt of Mechanical Engineering, Delft University of Technology*.
- Magel, E. E. & Liu, Y. 2014. On some aspects of the wheel-rail interaction. *Wear*, vol. 314, pp. 132-139.
- Meierhofer, A., Hardwick, C., Lewis, R., Six K. & Dietmaier, P. 2014. Third body layer-experimental results and a model describing its influence on the traction coefficient. *Wear*, vol. 314, pp. 148-154.
- Nadal, M. J. 1896. Theorie de la stabilite des locomotives. Part II: Mouvement de lacet. *Annales des Mines*, vol. 10, pp. 232-255.
- Niccolini, E., & Berthier, Y. 2005. Wheel-rail adhesion: laboratory study of “natural” third body role on locomotives wheels and rails. *Wear*, vol. 258, pp. 1172-1178.
- Pearce, T. G., Rose, K. A. 1982. Tangential force-creepage relationships in theory and practice, *Contact mechanics and wear of rail/wheel systems*. Vancouver, British Columbia.
- Polach, O. 2005. Creep forces in simulations of traction vehicles running on adhesion limit. *Wear*, vol. 258, pp. 992-1000.
- Pritchard, C. 1980. Traction between rolling steel surfaces. A survey of railway and laboratory experiments. *7th Leeds-Lyon Symposium on Tribology*.
- Reynolds, O. 1886. On the theory of lubrication and its application to mr. beauchamps tower's experiments, including an experimental determination of the viscosity of olive oil. *Phil. Trans. Roy. Soc. Of London*, vol. 177, pp. 157-234.
- Toumi, M., Chollet, H. & Honoré, Y. 2016a. Effect of elasto-plasticity on the creep force characteristics and the railway vehicle stability. *Proceeding of the 24th Symposium of the International Association for Vehicle System Dynamics (IAVSD2015), 17-21 August 2015, Graz, Austria*.
- Toumi, M., Chollet, H. & Honoré, Y. 2016b. Finite element analysis of the frictional wheel-rail rolling contact using explicit and implicit methods. *Wear*, Vol 366-367 p. 157-166.
- Vollebregt, E. A. H. 2014. Numerical modeling of measured railway creep versus creep-force curves with CONTACT. *Wear*, vol. 314, pp. 87-95.