Correlation between track geometry quality and vehicle reactions in the virtual rolling stock homologation process

K.U. Wolter
Deutsche Bahn AG
Railway Technology and Services
Integrated Systems Rail
Voelckerstrasse 5
80939 Muenchen
Germany

M. Zacher, B. Slovak
DB Netz AG
Technology, Interface Infrastructure
Voelckerstrasse 5
80939 Muenchen
Germany

Introduction
In order to enhance the competition of the railway sector in the European transportation market an interoperable network with interoperable vehicles has to be introduced. Since this could not be achieved in a single step, a constant transformation process towards a homogenous railway system has to be commenced. The European Community accelerated this process by implementing several Technical Specifications of Interoperability (TSI) for rolling stock, energy, infrastructure and signal & commands.

The TSIs refer to many European standards which have to be respected for the homologation of vehicles. For example the TSI RST refers to EN 14363 in which the requirements for safety against derailment, track loading and riding comfort are defined. In addition EN 14363 describes the conditions for on track tests. The track geometry quality has a significant influence of the test results. Therefore track geometry quality is classified in three categories QN 1, QN 2 and QN 3; whereupon QN 1 represents a good, QN 2 a medium and QN 3 a bad track quality level. The classification is based on the magnitude of a single track defect, on the standard deviation of the longitudinal level and the lateral alignment of the rails. Each test zone used for on track tests should include the following quality levels:

- 50 % of track geometry quality ≤ QN 1
- 40 % of track geometry quality between QN 1 and QN 2
- 10 % of track geometry quality > QN 2

The measured parameters for track geometry shall be filtered by a Butterworth filter of 4th order with a lower cut off frequency of 3 m and an upper cut of frequency of 25 m. According to EN 14363 the upper cut-off wavelength is valid for speeds up to 200 km/h. At higher speeds track geometry deviations with wavelengths higher than 25 m shall also be considered, but the correspondent values have not yet been determined.

Comparisons of test results and further investigations showed that the correlation between the magnitude of single track defects and the vehicle reactions in terms of wheel and rail forces are rather poor even if all criteria of EN 14363 are met. One reason is that the defect length is not taken into consideration.

The requirements on track geometry are not representative in all European member states, since the maintenance limits differ considerably. Therefore on-track tests for the homologation of vehicles are usually conducted in each member state in order to ensure a safe running behaviour of railway vehicles.
DynoTRAIN Project

In the 7th framework program of transport of the European Community a collaborative project called DynoTRAIN addresses the drawbacks mentioned above. The project DynoTRAIN started in June 2009 and will last four years. The objectives of the project are:

- to reduce costs and time of certification by improving cross acceptance of on track tests and introducing virtual certification
- to close the open points regarding track geometry and contact conditions in HS and CR TSI
- to establish standards for modelling and model validation for virtual certification

The project is divided into seven work packages (WP). In WP 1 stationary tests and on-track tests in four different countries (France, Italy, Switzerland and Germany) with five test vehicles were conducted. The test vehicles were a loco, a passenger coach, a 4-axle wagon with Y25 bogies and a 2-axle wagon with UIC double link suspensions. The wagons were tested in a fully loaded and in an empty condition. During the on track tests the track geometry quality, the rail profiles and the vehicle reactions were measured simultaneously. The data will be provided for WP 2, 3 and 5 for further analysis.

In WP 2 a better description of track geometry quality will be elaborated by means of the measured results in WP 1 and collected track data from infrastructure operators. The main objective of WP 2 is to assess the track geometry in terms of vehicle reactions such as wheel rail forces or riding comfort. Currently, there are two possibilities for solving this task. On the one hand the correlation between the vehicle behaviour and the track quality could be described by transfer functions in the frequency domain. On the other hand the maximum reaction of a vehicle could be predicted by an analytical transfer function dependent on characteristic of the track defect. Since both methods looks promising, Siemens will concentrate the work on the first method and DB on the second method during the project.

In WP 3 measured wheel and rail profiles have to be analysed and reference profiles for wheel and rail will be defined. Both reference profiles and measured profiles are used for the calculation of equivalent conicity maps for TEN lines. By means of equivalent conicity maps in-service limits of equivalent conicity for wheels and rails will be suggested.

WP 4 identifies specific local requirements for track loading and develops limit values related to infrastructure construction and maintenance in order to reduce the number of additional tests required for approval onto non-TSI compliant infrastructure.

WP 5 involves the state-of-the-art reviews of building and validation of multi-body railway vehicle models. It also specifies the requirements for an agreed process of validation of vehicle models for virtual certification.

WP 6 investigates how the use of agreed models and simulation methods in railway dynamics, in a combined process of calculation and on-track testing could extend the validity of the test results beyond the original conditions.

The purpose of the WP 7 is to ensure acceptance through coordination of the project work, so as to steer it towards convincing proposals for integrations with existing standards and homologation processes. Another aim is to support analyses whilst ensuring efficiency and cross-fertilisation with the results of previous and current research and enabling the creation of a solid platform on which to base future work.

The DynoTRAIN consortium consists of 25 partners whereupon UNIFE is responsible for the administrational part of the project. Deutsche Bahn AG (DB) is leader of WP 1 and WP 3. WP 2 is led by Siemens, WP 4 by RSSB, WP 5 by Bombardier Transportation, WP 6 by SNCF and WP 7 by DITS. The latter is a department of the University of Rome. In addition DB has a considerable amount of person month in WP 2.

This paper describes basic preliminary studies of DB carried out in WP 2. Further investigations will be conducted when the measured data from WP 1 are available.

Contribution of DB in WP 2

The main objective in WP 2 is to develop a method, which will map track geometry quality onto vehicle reactions. Such a mapping predicts the running behaviour of vehicles. The basic idea of the DB method is that only the maximum vehicle response of a single track defect is of interest, see
Consideration is compared with... In WP 2, the following parameters are chosen:

- track shifting force $\Sigma Y$
- quotient against derailment $Y/Q$
- track loading force $Q$
- vertical and lateral car body accelerations $z''$ and $y''$

The maximum vehicle response $R_{\text{max}}$ is linked to different parameters, such as magnitude and shape of the track irregularities in vertical and lateral direction, curvature $(1/R)$, speed $v$ and admissible cant deficiency $I_{\text{adm}}$. The running behaviour is also influenced by the contact conditions between wheel and rail, but this is not in the scope of WP 2.

**Figure 1:** Principle of DB method

In WP 2 the task is to find a function which predicts the maximum vehicle response dependent on several characteristic parameters described above. For example an linear analytical function of the following form

$$Q_{\text{max}} = a_1 z + a_2 z + a_3 \lambda_i + a_4 \lambda_r + a_5 v + a_6 (1/R) + a_7 I_{\text{adm}}$$

predicts the maximum $Q$ force of a wheel dependent on: the magnitude of the vertical track defect of left and right rail ($z$, $z$), the left and right defect length ($\lambda_i$, $\lambda_r$), the speed $v$, the curvature $1/R$ and the admissible cant deficiency $I_{\text{adm}}$. The unknown coefficients $a_1$ till $a_7$ depends on the vehicle in question and are determined by a linear regression. The linear regression is based on the results of a lot of simulations or measurements. In the case of simulations, test signals with different amplitude, wavelength and phase shifts could be used. Up to now in WP 2 of the DynoTRAIN project, only simulations have been carried out in order to check the feasibility of the method. In 2011 measured data from on-track tests in different countries with different vehicles, done in WP 1, will be investigated.

In order to apply a linear regression it is assumed that the vehicle behaviour could be linearised in a certain range of interest. Therefore it is important to concentrate on track defects which excite the vehicle considerably and cause high wheel/rail forces and car body accelerations. Otherwise the linear behaviour of the analytical function given above does not reflect the vehicle behaviour properly.

In a first step only the influence of vertical single track defects, independent of the track alignment, was investigated. This means in the function for $Q_{\text{max}}$ described above, only the first five terms will be considered. A single track geometry defect can be described through its amplitude, wavelength and shape. All of these parameters could then be combined in a reference function. The question which arises is how many reference functions have to be used in order to describe a general characteristic
of the track. It is clear that the number of reference functions should be as small as possible in order to avoid huge calculation effort.

Track record readings of longitudinal levels and lateral alignment showed similar track defects at distinct locations such as the transition from an embankment to a bridge or the through route in switches. In order to find similarities of track defects, real track geometric data were analysed by DB. In this part of work only track defects with amplitude bigger than 10 mm were taken into account. In total more than 5000 single track geometry defects have been analysed. The correlation coefficients of all possible combinations of different track defects were calculated and grouped in a corresponding matrix. As a result five groups of similar defect shapes could be defined. These defect shapes were used as reference functions. An example of similar track defects of two different groups and their typical representation (red curve) of each group is depicted in Figure 2.

![Figure 2: Single track defects and corresponding representative defects](image)

In the next step it has to be demonstrated that a reference function represents the real track defect sufficiently in terms of the running behaviour of a railway vehicle. For this reason a verified simulation model of the ICE power head has been used. The Q forces and vertical car body accelerations were calculated for the reference functions as well as for the real track defects. The simulations were carried out in straight track. An example of a time history plot of the Q force and the car body acceleration is depicted in Figure 3. The vehicle was excited by a real single track defect and the corresponding reference function. In this example even the shape of the time history plot is similar. In the diagrams the red curve is the vehicle response to the reference function, the blue curve the vehicle response to the real track defect.
Challenge G: An even more competitive and cost efficient railway

Figure 3: Q-force at the right and left wheel (top) and vertical car body acceleration at front and real bogie (bottom) for a single defect and for a corresponding reference function.

In the left diagrams of Figure 4, the correlation of the maximum and minimum Q forces of the leading wheelset due to different reference functions and real track defects is depicted. In the right diagram the correlation of maximum car body accelerations is plotted. The results are obtained by simulations with the multi-body-simulation tool Simpack. In the case of perfect correlation the points in the diagram lie on a straight line with an angle of 45°. For the ICE power head the correlation of the Q forces is 0.87.

Figure 4: Correlation of vehicle reaction of real track defect and reference functions

Furthermore a sensitivity analysis was carried out in order to find a dependency between the Q forces and the amplitude and wavelength of the reference functions. The amplitude and the wavelength of the reference function were varied in different steps. It is expected that small variations of amplitude and wavelength lead only to small variations in the Q forces. This is true as long as the wheel remains in contact with the rail. In the case of wheel lifts the Q forces increase rapidly when the wheel get in contact with the rail again. This is indicated by a sharp increase of the Q force in Figure 5. It can be
seen in the diagram that the variation of the wavelength has a bigger impact on the Q forces than the variation of the amplitude.

![Diagram showing Q force dependent on amplitude and wavelength]

**Figure 5:** Q force dependent on amplitude and wavelength

**Conclusion**

In WP 2 of the European DynoTRAIN project a new description of the track geometry quality will be developed. The main objective of WP 2 is to create a description of track geometry quality which is in good correlation with rolling stock behaviour. The DB method is based on a set of analytical functions in which the maximum vehicle reactions ($\sum Y, Y/Q, Q, y^*, z^*$) are dependent on the characteristic of a single track defect, speed, curvature and cant deficiency. The relationship between vehicle response and track excitation is determined by regression analysis. Either simulations or measurements can be used in order to provide the necessary input and output values.

In this paper reference functions are defined for the description of track geometry. Simulations showed that the vehicle reactions are similar due to reference functions as well as due to real track defects. In addition a sensitivity analysis is carried out in order to check the influence of wavelength and amplitude variations on the vehicle response. It could be shown that linearization is only possible in small regions, because of the non linear vehicle behaviour.

This paper describes work undertaken in the context of the DynoTRAIN project, Railway Vehicle Dynamics and Track Interactions: Total Regulatory Acceptance for the Interoperable Network (www.triotrain.eu). DynoTRAIN is a collaborative medium-scale focused research project supported by the European 7th Framework Programme, contract number: 234079.