Fast Analytical Wheel-Rail Contact Modelling for Realtime Capable MBS in HiL using MATLAB® Simulink®

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Abstract. Modelling wheel-rail contact within multibody simulation environments usually requires additional libraries or methods for handling creepage. Although specialised software such as Vtech CMCC CONTACT.dll allows for a precise contact discretisation it is time consuming and therefore not applicable for real-time capable models required for hardware-in-the-loop. Therefore, this paper introduces a new method that facilitates a fast wheel-rail contact analysis in MATLAB® Simulink® without introducing co-simulation. The new approach allows for the use of recorded real wheel/rail surfaces from laser scans and enables real-time simulations carried out on a dedicated Real Time Target Machine (RTTM) from Speedgoat. This paper presents the wheel/rail profile description method with the optional use of real laser scans and compares it to a Simpack model in a benchmark. By meshing rail profiles as surfaces and describing wheelsets as a point cloud in Simulink® Simscape, it becomes possible to simulate a hydraulic-mechatronic active steering system with individually suspended single-driven wheels, integrated into a modified tram in Zurich.

Keywords: Wheel-Rail Contact, Vehicle-Track and Train-Track Interactions, Track Structure and Modelling, Track Geometry, Software-in-the-Loop, Point-Cloud Approach, Traila Active Steering.

1 Introduction

1.1 Traila and the Active Steering technology

Established in 2018, the Swiss group Traila is developing a novel active steering technology [4], [5] for rail vehicles, based upon an onboard-sensor track-localisation system. The purpose is to improve the wheel-rail interaction and to reduce wear, tear, noise, and vibration. Using an inductive sensor package mounted close to the wheels, the position of a wheelset on the track is determined. Here, the sensors reliably detect the characteristic inner track edge. The position information from the sensors is then transmitted to X90, an industrial controller from the company B&R. It calculates a correction factor with the logic developed at Traila, which is then transmitted to an actuator. The actuator actively steers the wheelset on the track creating a closed control loop with the inductive sensors. Traila successfully demonstrated the use of its Traila Active Steering (TAS) system [6], [7] that led to the establishment of a relationship with Zurich public transportation service VBZ. In 2021 this resulted in the modification of a T2000 tram for the purposes of field testing the TAS. **Fig. 1** shows the axle bridge developed by Traila replacing the old rear bogie and allowing to actively control the yaw angle. It features two individually suspended and individually direct-driven wheels with two special-designed TSA asynchronous motors. A hydraulic actuator rotates the unit around the slewing ring using real-time position information. In addition, more than 40 sensors are being used for this special testing platform providing crucial data to improve the simulation models and advance TAS technology product.

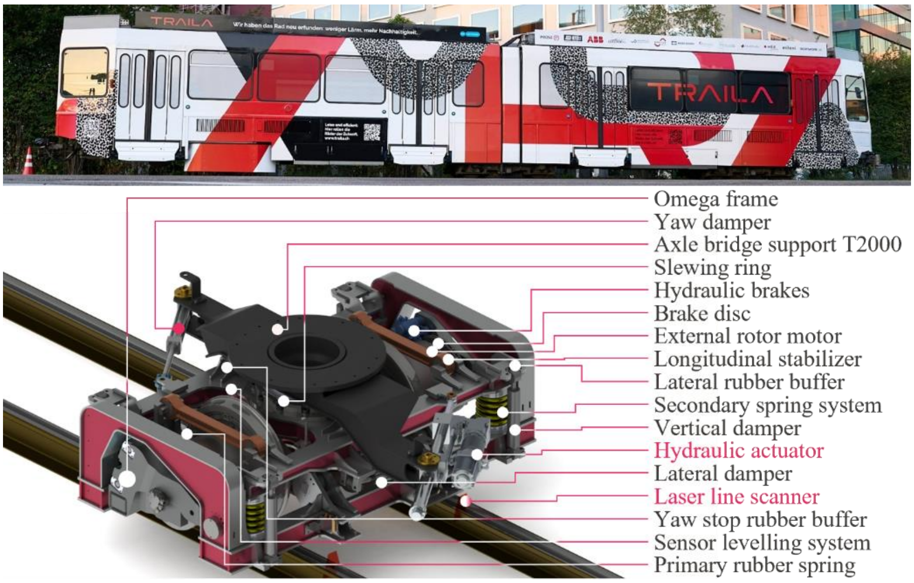

Fig. 1. Traila axle bridge with the TAS as a replacement for the rear bogie of the TX4

Currently, the Traila T2000 Test Tram (TX4) is being tested at the VBZ tram depot in Zurich Altstetten. Beneficial for the development of an actively steered wheelset for a tram within the framework of Traila's technology, the decision was made to perform as many virtual tests as possible in advance of testing on the TX4. This methodical approach to virtual testing is briefly described in the following sections.

1.2 Methodical development approach at Traila – SiL and HiL

Traila implements an Agile approach towards model-based engineering to ensure the rapid progress in development. The models are developed with MATLAB® and Simulink®, as this software suite offers the necessary freedom for modelling within the framework of the new TAS technology. Using Simulink® Simscape, a complete virtual tram was built. In addition, it also includes a hydraulic steering actuator and the TAS controller. The TAS logic is then tested against the virtual tram in a Software-in-the-

Loop (SiL) setup. After a successful SiL test, the physical tram model is compiled and deployed on Speedgoat's Real Time Target Machine (RTTM). Similarly, the control logic is transmitted to the X90 controller, which communicates with the RTTM via Powerlink in a Hardware-in-the-Loop (HiL) setup. Thus, the complex safety functions of the X90 can be tested along with the controller logic. The use of SiL guarantees the successful development of the control logic. In addition, HiL ensures that the control logic works as intended after being automatically converted and transferred to the X90. After making sure that the new software version meets the defined specifications and requirements, it can be deployed on the test vehicle TX4. Due to the given hardware and software architecture at Traila and the resulting technical requirements for SiL and HiL, the task was to develop a proper physical representation of the TX4 in MATLAB® and Simulink®. The challenge here was to create a real-time capable model with a sufficiently accurate representation of the wheel-track contact. While previous publications [2] describe two successful established approaches (integration of the external windows library CONTACT.dll [1] and point cloud approach [2]), the following sections deal with the latter, real-time capable approach of point cloud description.

2 Using Simulink® Simscape blocks for real-time models

2.1 Description of the novel Point-Cloud approach

As described above, the intention was to develop a method that exclusively uses MathWorks tools to enable a real-time capable simulation of the multiphysics model. With the Simscape library, a tool portfolio of blocks is available for modelling almost any complex cyber-physical system. The multibody library also offers contact modules. In this project, two problems had to be solved. Firstly, a suitable contact model had to be found that allows the wheel-rail contact to be modelled correctly, and secondly, a process had to be established that provides the track model and the wheel model for the multibody simulation. The approach presented here follows the three-dimensional contact modelling of a three-dimensional multiphysics model. The result of the work is summarised in the following library concept and the associated working method displayed in **Fig. 2**. The method is based on three newly created elements, a MATLAB® App, a Simulink® library block and an automatically assembled and configured subsystem block. In the developed App *Profile Generator*, the 2-dimensional profile of the track and wheel under consideration is described either analytically or numerically using real measurements (the latter functionality is described separately in this paper). This profile is passed to the *Track Builder*, a specifically developed multifunctional library block. The concept behind this is the extrusion of a constant or variable track cross-section profile along a spline described by support points. The block prepares the exact track section description analytically and then automatically builds the displayed *Track Section* as a subsystem block at the push of a button. The exact procedure is described later. Therefore, a global track coordinate system is placed, a segmented piece of surface model is properly positioned to describe the track, and this is then connected to the *Spatial Contact Force* block (SCF). The subsystem, which combines these repetitively contained blocks, is finally integrated into the overall tram or multiphysics model.

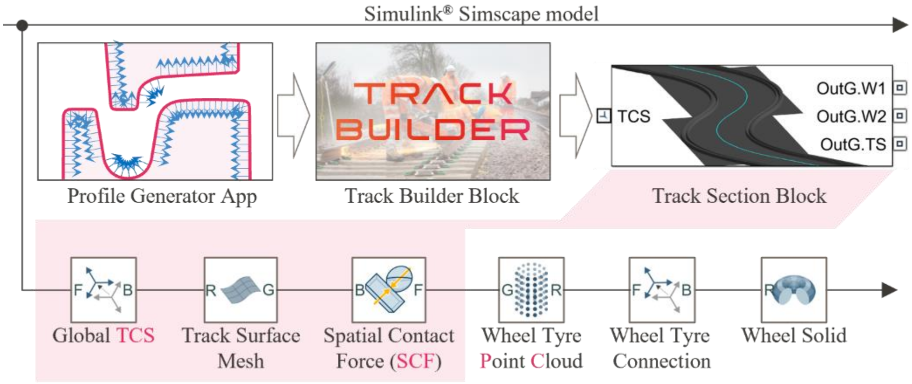

Fig. 2. Elements of the novel Point-Cloud approach in Simulink® as described in the text

On the spline, a Track Coordinate System (TCS) can freely move without friction. Any number of wheels can be placed on the surface mesh of the analytically described track. Due to a special restriction of the Simscape Multibody *Solid* blocks, which only allows concave volume models, the wheels need to be modelled with the Simscape Multibody *Point Cloud* block. This enables contact analysis with arbitrary geometries. However, up to MATLAB® version 2023a this approach does not allow physics inputs or outputs to the *SCF* block when a point cloud geometry is used. This creates limitations on the customisation of the wheel-rail contact model, regarding the implementation of a creep representation. These limitations are overcome in the new 2023b software version to provide a simplified but effective creep representation. To create an accurate enough physical contact representation for HiL applications, the model parameters are currently fine-tuned with Simpack and the external library CONTACT.dll [1], [3]. By calibrating the friction coefficients of the *SCF* block, the so tuned model can be applied for limited cases but used for generating a wide range of HiL scenarios. This approach allows for arbitrary track surface meshes and wheel tyre point clouds, as well as for implementing defects recorded with laser line scans as described later in this paper.

2.2 Profile Generator

The profile generator uses points, lines, and circular arcs to generate G1 continuous profiles [8]. It can also upload points from a laser line scan and structure them into a profile slice. The idea is to synthesise geometrical profiles to be used by the Track Builder. Although there are several ways to synthesise profiles [8], [9], a simple approach is to use vector algebraic equations. In **Fig. 3** the approach is demonstrated for a grooved rail profile 60R2 used in the Zurich network. The geometry is divided into 13 curve segments of different curvature, numbered from right to left. When using the app, the idea is to create a profile vector with lateral y- and vertical z-coordinates of points based on a line point density such that the origin is at (0,0) mm, which is the reference gauge point for the Track Builder. Providing the point P1 followed by a vertical line, a circular arc with a radius and a mathematically positive rotation follows for segment two. Each segment, starting at segment one and ending at segment thirteen has unique properties, e.g., segment six with a mathematically negative rotational direction.

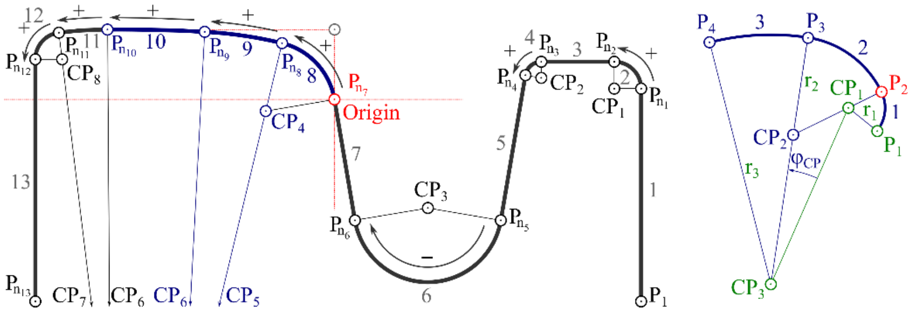

Fig. 3. Left: G1 continuous rail profile 60R2; Right: model for consecutive arcs of circles

However, it is challenging when G1 continuity is to be ensured for radius transitions with several following circular arcs. For example, segment 8 along with segments 9 and 10 is such a case. The mathematical approach chosen at Traila is shown in **Fig. 3** on the right. Inputs are P_1, the circle centre points CP_1 and CP_3 as well as the three radii r_1 to r_3 of the consecutive arcs. First the circle centre point CP2 is calculated with the help of eq. 2 using the angle φ_{CP}, which is obtained by applying the cosine law in eq. 1.

$$\varphi_{CP} = acos\left(\frac{(r_3 - r_2)^2 + |CP_1 - CP_3|^2 - (r_2 - r_1)^2}{2 \cdot (r_3 - r_2) \cdot |CP_1 - CP_3|}\right) \tag{1}$$

$$CP_2 = CP_3 + \frac{r_3 - r_2}{|CP_1 - CP_3|} \cdot \begin{bmatrix} cos(\varphi_{CP}) & -\sin(\varphi_{CP}) \\ \sin(\varphi_{CP}) & \cos(\varphi_{CP}) \end{bmatrix} \cdot (CP_1 - CP_3) \tag{2}$$

$$P_2 = CP_2 + \frac{r_2}{|CP_1 - CP_3|} \cdot (CP_1 - CP_3) \tag{3}$$

Since, due to G1 continuity, the three points CP_1, CP_2 and P_2 lie on a line, the result can be determined in the last step using eq. 3. Following this principle, the *Profile Generator* app calculates all segments of a track or wheel profile. When loading a laser line scan, the points can be automatically ordered, filtered, and cut. Each profile created in this way corresponds to a slice. Different profiles can be determined; for example, track changes or defects can also be mapped sequentially. These slices are used by the Track Builder to mesh a track surface and for the point cloud representing the wheel tyre.

2.3 Track Builder

Extruding variable profile slices along a spline. The underlying concept is shown in **Fig. 4** and is based on extruding arbitrarily shaped two-dimensional profiles along a spline. The concept works in two steps: firstly, the modelling of the spline on which the TCS slides without friction and secondly, the arrangement of corresponding profile slices in the normal n_i and binormal b_i direction of the respective spline point SP_i.

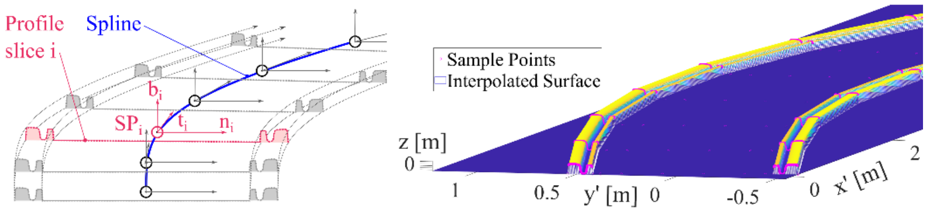

Fig. 4. *Track Builder* principle: extruding variable profile slices along a spline

In the first step, a track section is modelled by connecting straight lines and circular arcs or clothoids with G1 continuity. Here, also shallow sections in the track can be defined, where the wheel runs on its outer diameter. In the future, it will be possible to define crossings, ascents, or descents. With the help of analytically described spatial support points, a Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) spline is created. In the second step, any profile can be extruded along that spline. This profile can either be the analytically described one from the *Profile Generator* or a real profile from a measurement campaign. For each spline point, a corresponding profile is loaded and correctly positioned to match the normal and binormal directions. The surface mesh is automatically created through interpolation with a given mesh density in both longitudinal and lateral direction. **Fig. 4** shows how it impacts the quality of the track surface. Various implemented strategies allow either to load an individual profile slice for each spline point or to transform from one two-dimensional profile to another over a defined length of the spline using various transition functions. A current limitation of this approach is that only a rectangular mesh can be created in Simulink®. Thus, if the entire track section were generated in one step, millions of unused points (for contact analysis) would be produced due to the fixed-point density. To avoid this, an algorithm was implemented that automatically performs a minimum area optimisation for each track section (straight line, curve, clothoid). Meaning, it fits the respective track section into the smallest possible rectangle in the x-y plane. In this way, different sections can be joined with a minimum of mesh nodes. Another auxiliary algorithm controls the mesh density for straight line sections to avoid unnecessary middle points in longitudinal direction. In a final step, all necessary blocks are automatically placed, connected, and parameterised according to the selected settings in the block mask.

Use of analytical profiles from the *Profile Generator*. Fig. 5 shows an analytically described 60R2 profile (the upper part of the profile gets in contact with the wheel) of a curve section with a 15 m radius over an angular span of 30 degrees. The mesh density was set to 150 points per metre in the longitudinal direction and 300 points per metre in the lateral direction. Longitudinal x' and lateral y' refer to the transformed coordinate system (hence the ') of the minimum projected base areas of the x-y plane.

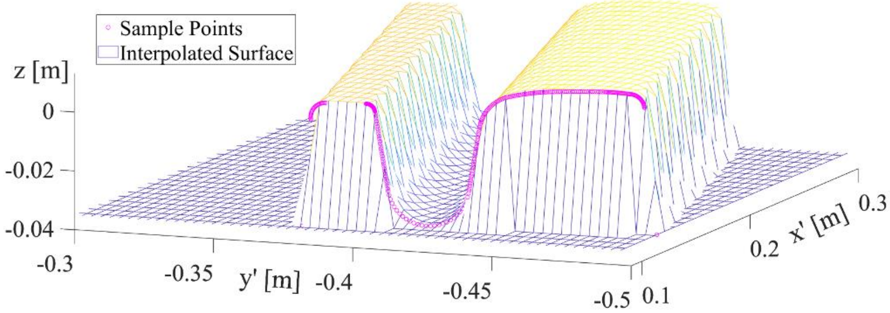

Fig. 5. Result of the meshed track surface with a grooved 60R2 profile

Even though polygonization effects can be seen in the image, this is only relevant for the simulation if the wheel has a larger angle of attack during contact determination. Since most models are intended for SiL and HiL applications, this is avoided by the active steering. The geometrical inaccuracies in the contact model can be identified as underlying vibration, which can be filtered out of the results accordingly. However, the influence of the mesh fineness on the computation time must also be considered, e.g., through an initial sensitivity analysis of the mesh and model parameters.

Use of real-world data from laser scans. As Traila uses the TX4 to test and deploy its TAS, there is a unique opportunity to use real-world data to extend and improve the simulation models. The TX4 was equipped with a total of 4 Wenglor laser line scanners, which record clocked line scans. Hence, a tool has been developed to use profile slices of a real-world track via laser scanning. Taking into account the position of the sensors, each laser sends and receives a scanning line for each movement corresponding to one 128th of the wheel circumference (a value chosen by Traila using rotary encoders within the TSA motors). This way, the lines are almost equidistant, knowing that the absolute position error increases with creep and over time. But it simplifies track detection because the trigger is independent from the tram speed. Several test campaigns have been carried out from July 2022 until May 2023 with the TX4 recording data at the VBZ tram depot. The private loop contains straight segments, a range of curves, various crossings, different rail profiles (grooved and vignole) and switches (including a crossing with a standard rail gauge track). Thus, it represents most of the challenges the TX4 must face during public network testing. **Fig. 6** shows the collected data postprocessed via MATLAB®. With the help of special inhouse scripts, the raw laser data is organised and then analysed to correctly set the profile origin point and to remove the influence of the steering angle and lateral motion. Therefore, each profile slice is scanned and the edge most likely to be a trace edge candidate among all points is selected through a series of weighted penalty criteria. The algorithm avoids wrong decisions at switches, crossings, defects, or multiple lines by storing the previous origin point. Here, geometric distortions have no influence on the weighted penalty criteria mentioned above.

With the correct origin point of each profile slice, it is then easy to filter and search for distinctive features (such as the lip of the groove) in the track.

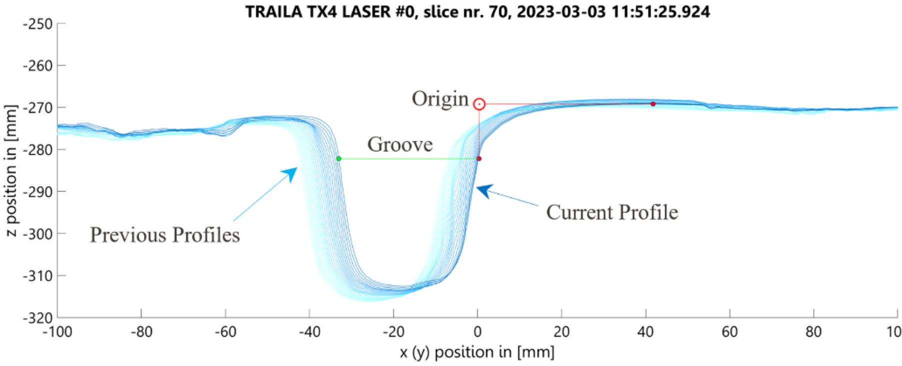

Fig. 6. Readings from test campaigns with real-world laser data

Since each profile slice has an approximately equidistant position (for the TX4 17.4 mm in longitudinal direction) in relation to the track and can therefore be uploaded to the track builder in the form of matrices of lateral y-profile vectors and vertical z-height profile vectors for each track side. The data is then automatically assembled into a 3D mesh by the *Track Builder* using the afore mentioned approach. Thanks to this, basically every track surface can be scanned and virtually deployed to a SiL/HiL model. The track spline (along which the profile slices are extruded) can be determined via GPS or CAD-based maps with all the necessary features. The result is shown in **Fig. 7**.

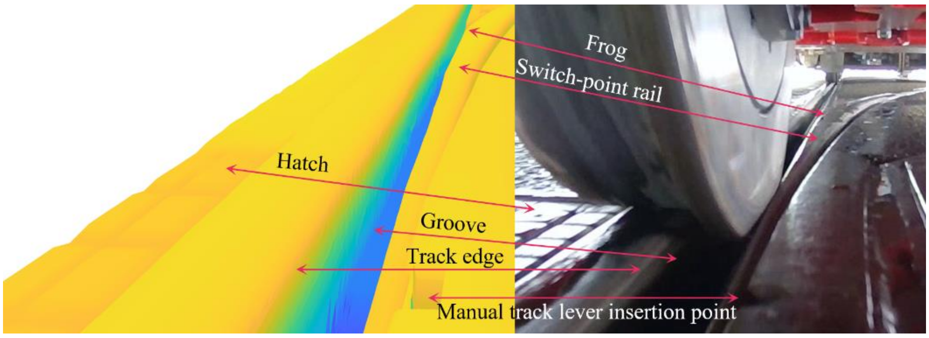

Fig. 7. Left: meshed surface in MATLAB®; Right: real footage from the TX4

3 Comparison/Results

A simplified 3D model of the TX4 was developed using the Point-Cloud approach. The aim was to compare the analytically generated track surface with the laser scanned imperfect surface model. The latter has been recorded in Altstetten (Zurich) in May 2023 with the lasers mounted on the TX4. The model is a dynamic representation of the TX4, with an axle load of 9.5 t. A validation exercise has been conducted to tune the Point-Cloud model with the analytical track against the same model built in SIMPACK®. As a result of this correlation, parameters such as dynamic friction coefficient as well as the lateral and vertical damping of the contact have been parameterised to match the behaviour seen in SIMPACK®. For the comparison between the analytical track and laser scanned profiles, a track with 1 m gauge and a 60R2 profile (used in Zurich) has been chosen. The track spline starts with a 50 m long straight section, which turns into a curve with a radius of 50 m and an angle of 30°, followed by another 50 m long straight section. A simple PID controller keeps the vehicle speed at 5 m/s and a second one minimises the lateral position. Thus, it controls the steering angle (yaw angle) based on measurements from an inductive sensor. **Fig. 8** shows both lateral and vertical displacement of the left wheelset coordinate system running on the analytical profile (in red) and the laser scanned track (in yellow). The overall behaviour is similar; however, it is clearly noticeable how the laser scanned track is more irregular than the analytical one due to real-world track imperfections. Small perturbations in the analytical profile are due to the combination of mesh and point-cloud density. This effect is still present in the laser scanned track, but it is negligible compared to the perturbations due to real imperfections in the track. Therefore, the simulation with the laser scanned track can give insights on how the system would dynamically react in the real world.

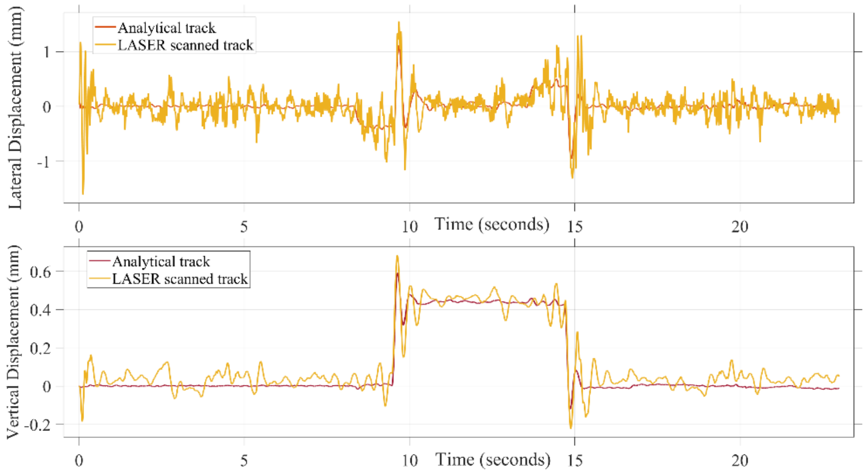

Fig. 8. Comparison between analytical approach and laser scanned track

4 Summary and Outlook

The paper presents a novel methodology for running multiphysics models of rail vehicles in real-time, utilizing the MATLAB® Simulink® library ecosystem. This enables such models to run on real-time computers in a HiL test environment. Although not

explained in this paper, Traila has successfully deployed these models as real-time applications on a real-time machine (HiL environment). Results will be presented in the accompanying presentation.
The paper described an implementation of a contact model with the help of analytical and partially numerical algorithms in such a way that it allows multi-physical models to be calculated quickly. The method presented is currently limited in properly calculating the creepage in the wheel-rail contact. Since the model is designed for use on HiL, the global behaviour model of the tram vehicle is given higher priority than an exact calculation of the creepage in the wheel-rail contact. Traila is aware that this method is currently associated with restrictions in terms of creepage, that will be resolved in the future. Also, the models are limited in terms of their maximum degree of freedom and lateral dynamics in such a way that too many contact changes jeopardise the real-time capability. However, the entire model with the controller or alternatively a passively safe four-wheeled bogie can easily be calculated in real time.

Thanks to the approach, it is possible to use a virtual tram model and even a HiL mock-up to determine the potential benefits of an active steering system based on real track scenarios. Thus, the system dynamics and the required controller settings can be estimated without the need for a complex test vehicle. Alternatively, and for the midterm strategy of Traila, this method will dramatically reduce the time to deployment of a novel active steering system into into a new bogie design or by retrofitting the system into an existing rail vehicle.

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