Application of virtual certification techniques to vehicle design and track maintenance

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APPLICATION OF VIRTUAL CERTIFICATION TECHNIQUES TO VEHICLE DESIGN AND TRACK MAINTENANCE

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Abstract

Virtual certification partially substitutes by computer simulations the experimental techniques required for rail vehicle certification. In this paper, several works were these techniques were used in the vehicle design and track maintenance processes are presented. Dynamic simulation of multibody systems was used to virtually apply the EN14363 standard to certify the dynamic behaviour of vehicles. The works described are: assessment of a freight bogie design adapted to meter-gauge, assessment of a railway track layout for a subway network, freight bogie design with higher speed and axle load, and processing of the data acquired by a track recording vehicle for track maintenance.

1 INTRODUCTION

Current methods for railway vehicles certification demand both high economic and high temporal costs, which increase the price of vehicles and delay their commissioning. These costs could be reduced by applying virtual certification techniques. Virtual certification (1), (2), (3) can be considered as the complete or partial substitution of the experimental techniques required by current standards for rail vehicle certification, by computer simulations. To that end, both finite element calculations and dynamic analysis techniques of multibody systems can be used.

The introduction of these virtual certification techniques would allow to: replace part of the experimental tests, for new vehicles, by dynamic simulations with properly validated models; replace almost all the experimental tests by simulations, for modified vehicles close to another vehicle already certified; and extend the approval to other countries, for vehicles already certified in one country, just performing the simulations needed to consider the changes in the track characteristics or in the operating conditions (4).

This could significantly save both money and time in the costly process of new vehicles certification, which would benefit manufacturers, operators and railway administrations. Furthermore, other operating conditions and environmental factors that cannot be taken into account in the physical tests could also be considered. However, at present this method of certification is still not accepted by the relevant authorities.

1.1 Virtual certification methodology for assessing the dynamic behaviour of railway vehicles

To carry out this process, a multibody system model of the railway vehicle to be certified is built. This model is mainly defined from the data provided by the manufacturer, and its unknown parameters can be initially estimated from the values stored in a database with values of different real trains. Next, some simulations are performed using proper track layouts and operating conditions to validate the vehicle model by comparing simulation results with experimental measurements. After this, the vehicle model is modified to match simulation results with test results.

Once the model is validated, the operating conditions, the track layout and the track quality are modified in order to satisfy the related indications of the EN14363 standard. In particular, the track layout should include four types of zones, with different curve radius ranges, each one composed by a set of sections, adjacent or not, that would satisfy some requirements which are summarized in Table 1.

Type of zone	Running speed [1] [km/h]	Curve radius [m]	Cant deficiency [2] [mm]
Straight track, or track with very large radius curves	$V = 1.1 \cdot V_{lim}$	-	$I \leq 40$
With large radius curves	$V = 1.1 \cdot V_{lim}$	$R > 600$	$0.75 \cdot CD_{adm} \leq CD \leq 1.1 \cdot CD_{adm}$
With medium radius curves	According to track layout	$400 \leq R \leq 600$	$0.75 \cdot CD_{adm} \leq CD \leq 1.1 \cdot CD_{adm}$
With small radius curves	According to track layout	$250 \leq R < 400$	$0.75 \cdot Cd_{adm} \leq CD \leq 1.1 \cdot CD_{adm}$

Note [1]: V_{lim} = maximum operating speed of the vehicle. [2]: CD_{adm} = Admissible cant deficiency.

Table 1 EN 14363 indications relating to track layout

After the relevant simulations are carried out, the results of those variables that reveal the dynamic behaviour of the vehicle are stored. In particular, the variables related to running safety are the sum of guidance forces ΣY, the Nadal

index Y/Q, the bogie lateral acceleration $\ddot{y}_s^+$, and the carbody lateral acceleration $\ddot{y}_s^*$; The variables related with track fatigue are the vertical wheel load Q and the lateral wheel force Y; and the variables related with running quality are the carbody lateral acceleration $\ddot{y}_q^*$ and the carbody vertical acceleration $\ddot{z}_q^*$.

Finally, simulation results are processed following the indications of the EN14363 standard (see Figure 2), and an estimated maximum value is so obtained for each of the different indexes used to assess the vehicle safety, track fatigue and running quality. These maximum values are then compared with the limit values proposed by the standard for each index. The vehicle dynamic behaviour is considered to be suitable if the estimated maximum values obtained for all indexes are below its related limit value.
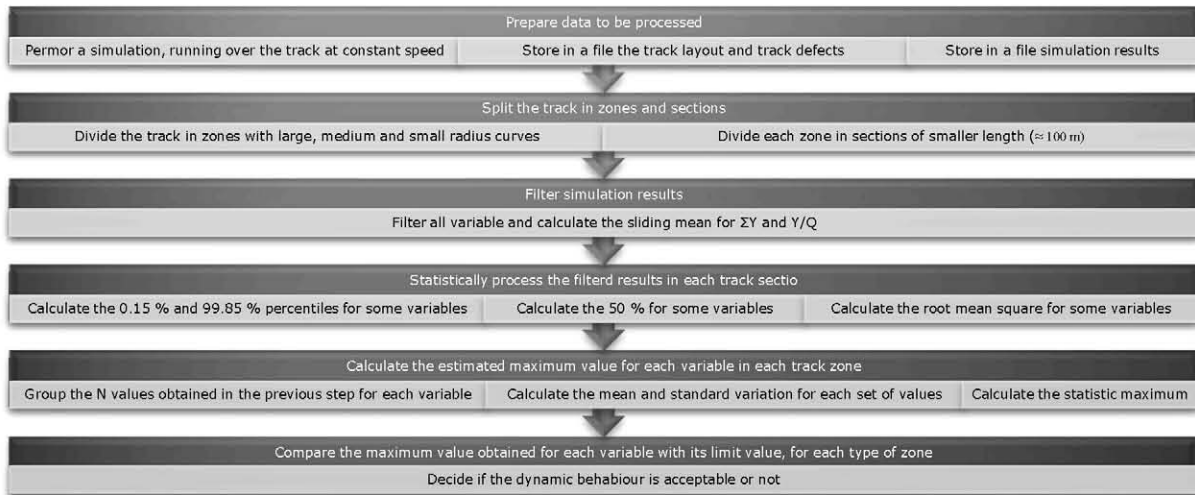
Prepare data to be processed		
Permor a simulation, running over the track at constant speed	Store in a file the track layout and track defects	Store in a file simulation results

Split the track in zones and sections	
Divide the track in zones with large, medium and small radius curves	Divide each zone in sections of smaller length ($\approx 100\,\mathrm{m}$)

Filter simulation results
Filter all variable and calculate the sliding mean for ΣY and Y/Q

Statistically process the filterd results in each track sectio		
Calculate the 0.15 % and 99.85 % percentiles for some variables	Calculate the 50 % for some variables	Calculate the root mean square for some variables

Calculate the estimated maximum value for each variable in each track zone		
Group the N values obtained in the previous step for each variable	Calculate the mean and standard variation for each set of values	Calculate the statistic maximum

Compare the maximum value obtained for each variable with its limit value, for each type of zone
Decide if the dynamic behabiour is acceptable or not

Figure 1 Scheme showing the mathematical processing of simulation results

2 APPLICATION OF VIRTUAL CERTIFICATION TECHNIQUES

In this paper, the authors present several works of different nature, where virtual certification techniques were used to treat several facets related to rolling stock design and track maintenance. In particular, dynamic simulation techniques of multibody systems were used in order to virtually apply the European standard EN14363 (5). This standard uses field tests to certify railway vehicles, regarding its dynamic behaviour from the point of view of safety, track fatigue and ride quality. In the following, the different projects developed by application of this working methodology are described.

2.1 Assessment of a Y-25 freight bogie design, adapted to meter-gauge

The aim of this work was to ensure the proper dynamic behaviour of a new freight container wagon, for a maximum operating speed of 100 km/h, with a bogie based on the classic Y-25, but adapted to meter-gauge. However, the railway administration where this bogie was going to run did not have enough track length with straight sections and large radius curves to properly certify the vehicle following the experimental techniques specified on the EN14363 standard. Thus, to have a higher guarantee, experimental techniques were replaced by simulations in all the track sections not available in actual practice. To perform these simulations, a vehicle model was generated (see Figure 2, left), using the data provided by the manufacturer, for both tare and full load.
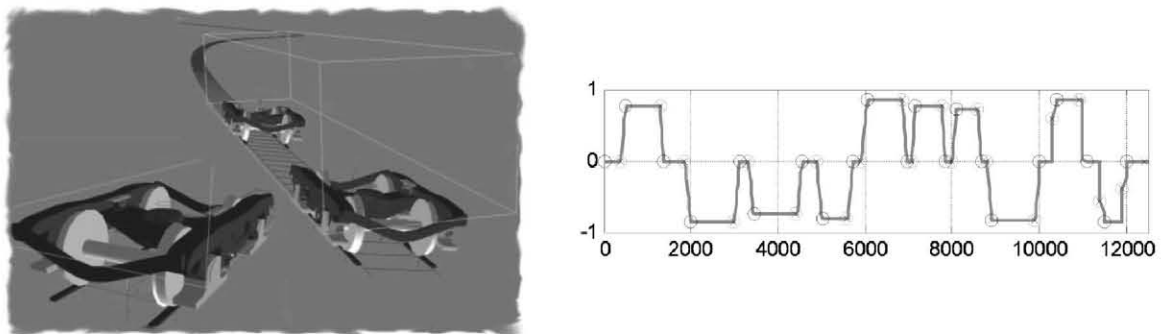

Figure 2 Vehicle model (left) and track curvature for the track model with large radius curves (right)

As no suitable real track was found, a fictitious 12 km track model with straight sections and large radius curves was also defined, following the indications stated in the EN14363 standard regarding the features required for both track layout and track quality. Figure 2 (right) shows the curvature of the track model used to simulate the vehicle dynamic behaviour. Track cant was defined so that at 110 km/h the cant deficiency stayed within the range stated in the standard.

Once the appropriate simulations were performed, simulation results were processed following the indications of this standard, so obtaining an estimated maximum value for each of the analysed variables, which was then compared with the limit value provided by the standard. This way, it was checked that the new bogie design was suitable from the dynamic point of view, and nowadays it has been running on metric-gauge tracks for several years.

2.2 Assessment of a railway track layout for a subway network

On the excavation phase of a subway tunnel, the projected track layout was unintentionally modified due to an error on the path of the tunnel boring machine. As no real track was installed yet inside the tunnel, virtual certification techniques were used in order to determine the scope of this error.

Track models were defined in accordance with both the theoretical and the real layouts (see Figure 3, right), using the data directly extracted from the track drafts (length, curve radius, cant, etc.). As for the vehicle, a standard subway three-car model was used (Figure 3, left), with maximum running speed and axle load like those of the vehicles that would run on the new line, which were not yet purchased. The vehicle geometry, the mass properties of the bodies and the elastic properties of the primary and the secondary suspensions were obtained from a bibliographic database, from which a vehicle with features close to that of the vehicles which were going to run on that line was chosen.
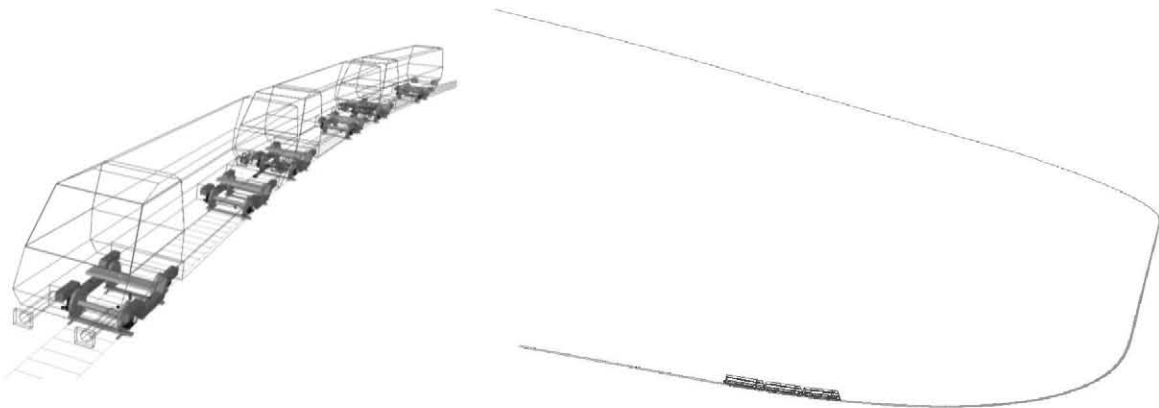

Figure 3 Vehicle model (left) and track layout (right)

Several preliminary simulations were performed to determine the most critical running scenarios. In this way, the most critical loading state for this analysis was found for the full loaded vehicle. Next, several simulations were performed using different running speed profiles, with the velocity ranging from 45 to 55 km/h in the track section were the tunnel boring machine was deviated (Figure 5, left). Simulation results were processed following the indications of the EN14363 standard, finally concluding that the layout deviation had a small influence on vehicle safety (see Figure 4, right), on track fatigue and on ride quality.
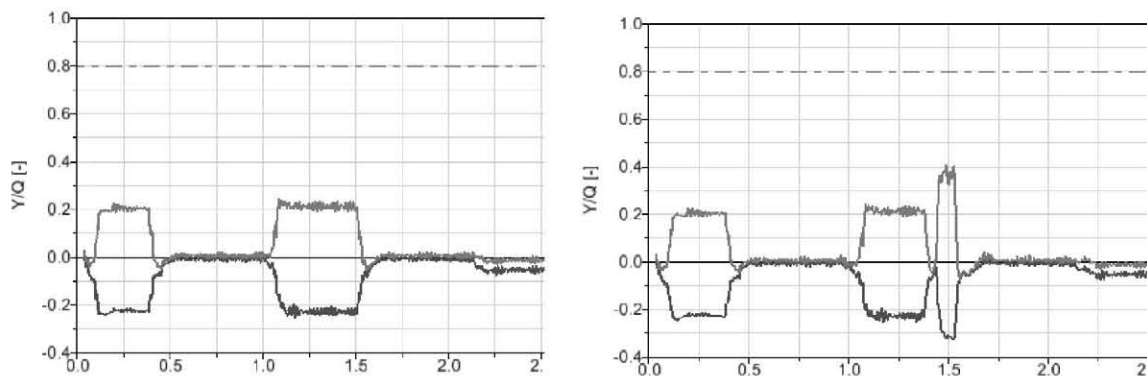

Figure 4 Detail of the derailment index obtained for theoretic (left) and new (right) track layouts

As an example, Figure 5 (right) shows the results obtained at three different running speeds for several of the safety indexes (SEG), track fatigue indexes (FAT) and running quality indexes (CON) stated in the standard. In order to

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include all these results in a same plot, they are presented as a percentage of the limit values proposed by the standard. These results were used to decide whether or not the running speed should be modified when passing over the curve with the modified radius.
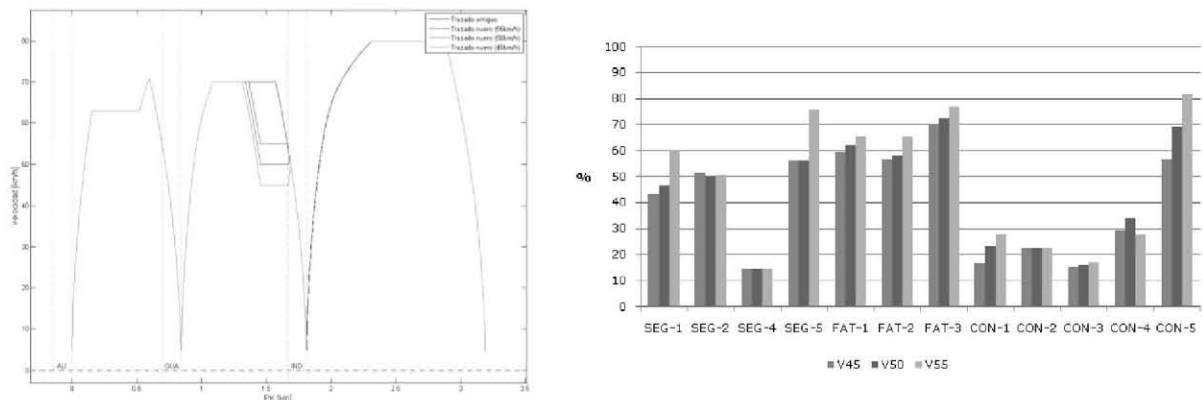

Figure 5 Velocity profile (left) and indexes to assess the dynamic behaviour for three running speeds (right)

2.3   Freight bogie design with higher speed and higher axle load

A freight 60 feet container wagon, with Y-21 bogies (with similar features than the Y-25 bogie, but adapted to Iberian-gauge) and a proven satisfactory dynamic behaviour at 100 km/h, was intended to be operated at 120 km/h. In order to increase its operating speed from 100 to 120 km/h, experimental certification tests were performed, following the EN14363 standard. The results of these tests revealed high lateral carbody acceleration in track sections and large radius curves in tare and asymmetric load state (with just a single 30 foot container), and therefore the vehicle was discarded for 120 km/h.

After the failure of the experimental tests, virtual certification techniques were used in order to find the most suitable option to adapt the bogie design for higher running speeds. A vehicle model composed of two wagons and a locomotive was defined (Figure 6, left), with three load states: tare, full load and asymmetric load. This model was created using the vehicle data provided by the manufacturer, and then it was validated with the results obtained in the previous certification tests. As the features of the test track were not accurately enough known, three fictitious track models were also defined, of 12 km length each, for large, medium and small radius curves. These track models were respectively run at 132, 93 and 66 km/h.

As the limit values stated in the standard were only slightly surpassed, it was decided to introduce small modifications on the bogie design, intending to preserve both the original bogie-frame structure and the suspension features. In a first stage, three different wheel profiles, with lower effective conicity than the original wheel profile were considered in the simulation models, getting higher vehicle stability, suitable to reach the target speed. However, due to the satisfactory wear behaviour of the original wheel, other design options were also considered, as the suppression of the ±1 mm longitudinal clearance of the bearers. Good simulation results were obtained again, achieving higher stability in straight track and large radius curves sections, not significantly worsening guiding performance in small radius curves.

Figure 6 (right) shows the results obtained for the lateral carbody acceleration in full curves (Cv), transition curves (Tr) and straight track (St) for all the different scenarios considered with an empty vehicle. The simulated scenarios were: A, original wheel with bearer clearance; B, original wheel without bearer clearance; C, D, E, other wheels with bearer clearance.
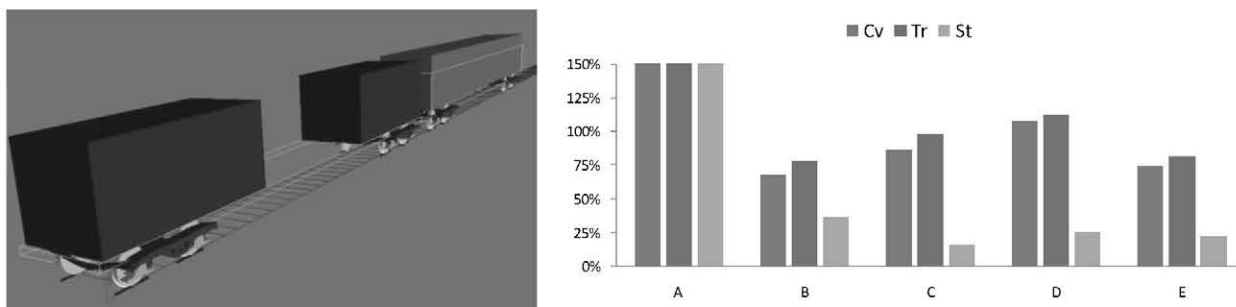

Figure 6 Vehicle model (left) and simulation results for lateral carbody acceleration in tare (right).

Once the virtual certification stage was finished, the new design was subjected to experimental certification tests again, separately checking the two considered design options:

- Replacing the original wheel by other with lower equivalent conicity, but maintaining the bearer clearance

- Suppressing the bearer longitudinal clearance, but maintaining the original wheel profile

As the real features of the track used in the tests were initially unknown, both the track layout and the rail defects used in the simulations were different from those of the track used in the measurements, so that slight differences were found when comparing simulation results with measurements. Nevertheless, the experimental tests confirmed the good results observed in the simulations, and the new design was finally accepted to run at 120 km/h on Iberian-gauge tracks. Figure 7 shows the comparative results between measurements and simulation for a full loaded vehicle running on tack zones with large (RL), medium (RM) and small (RS) radius curves, for both full curves (Cv) and transition curves (Tr).
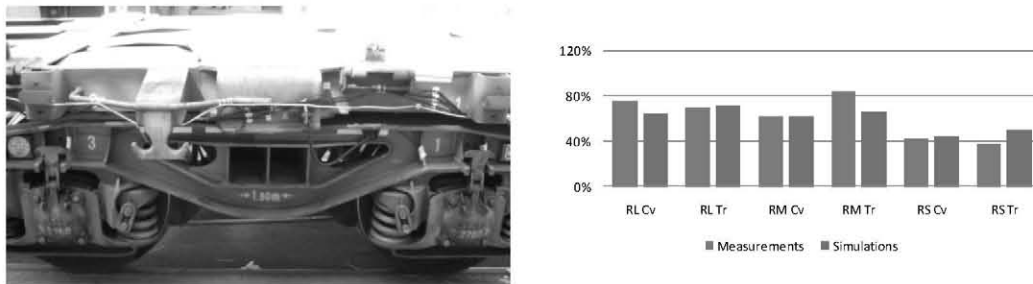

Figure 7 Sensor installation (left) and comparative results obtained for lateral carbody acceleration in simulations and measurements (right) for full load.

At present, virtual certification techniques are being applied again, in order to obtain a new design evolution, suitable to increase the running speed from 120 to 140 km/h, as well as to increase the axle load from 20 to 25 ton. Naturally, these increments require modifications both on the bogie-frame structure, and on the suspension features.

2.4   Processing of the data acquired by a track recording vehicle for track maintenance

At present, the authors, in cooperation with Metro de Madrid, are also using virtual certification techniques as an aid in the planning of track maintenance operations, in a project co-financed by the CDTI. In particular, track models of a whole subway network are being defined from the real data (curvature, cant, gauge, horizontal alignment and vertical alignment) measured by a track recording vehicle. A database with the models of all the vehicles running on the network is also available. These models are parameterized (Figure 8), and can be easily modified from a text file, not needing to access the multibody systems simulation program.
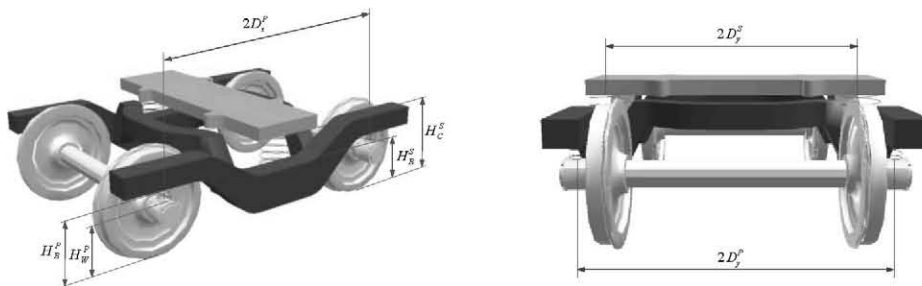

Figure 8 Detail of the vehicle parametric model.

All vehicle models were validated against measurements, sometimes by the own manufacturers, and sometimes by the authors. To validate these models displacement sensors (Figure 9, left) were used to measure the vertical and lateral movements of the primary and secondary suspensions, as well as accelerometers to measure the lateral and vertical accelerations of the carbody and the lateral accelerations of the bogie. Figure 9 (right) shows the comparative results obtained for the vertical displacement of the primary suspension. Measurement results are shown in dark green and simulation results in light green.
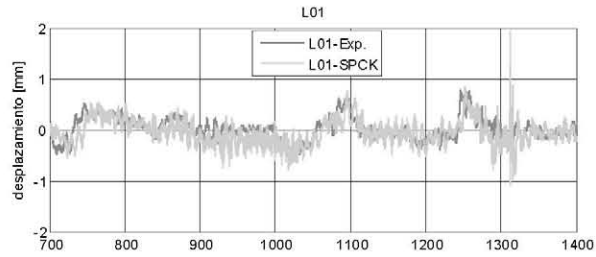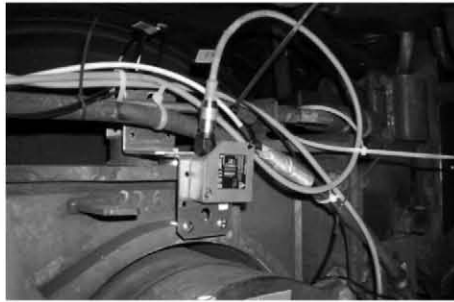
Figure 9 Vertical displacement of the primary suspension: sensor (left) and comparative results (right).

On each track model, the dynamic behaviour of the vehicles was simulated at commercial operating speeds, using a variable velocity profile as a function of the track position.

As in other cases, simulation results were processed according to the EN14363 standard, but with a couple of exceptions: this time, the mathematical treatment stated in the standard was not applied as a whole, as it was intended to know the vehicle behaviour in each track point, and not its global behaviour on the complete line; in the same way, the limit values suggested by the standard were not directly applied, as the vehicles do not run at the maximum allowed speed, but at the commercial operation speed.

Due to the large length of the network to simulate, a computer program was developed to automate the process. This program has two different modules: pre-processing and post-processing.

The pre-processing module reads the track recording data files, and automatically creates the track models for each track section between two stations. This module also combines these track models with the proper vehicle model and the proper operating speed profile. It also automatically launches all simulations, in sequential form, and exports simulation results, also automatically, for their further treatment with the post-processing module.

The post-processing module reads the result files for all the track sections between two stations for a given line, connects all these results, and statistically processes the results of the whole line following the recommendations of the EN14363 standard, but with limit values freely defined by the user. It also automatically generates a report file with the most significant results obtained for the whole line, and plots these results as a function of the track position, or directly show them over the network plane, using a colour code (see Figure 10).
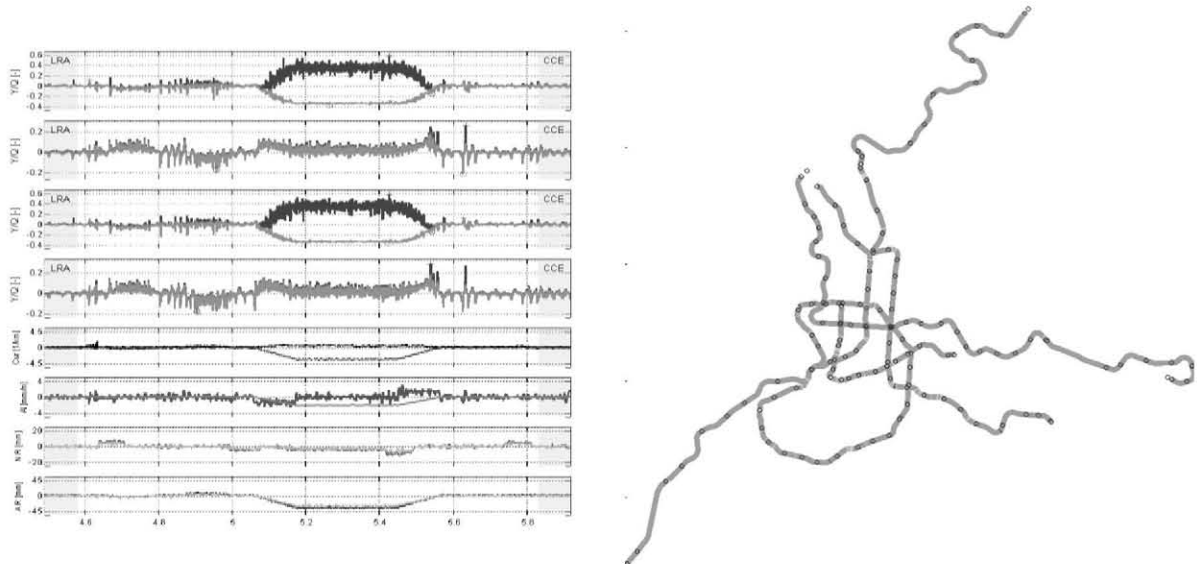

Figure 10 Simulation results: plot (left) and results over the network plane (right).

From the results obtained in the simulations, the track sections where the vehicle behaviour is unsuitable, and thus a track maintenance operation is needed, can be located. Besides, using recording data from different dates, track quality evolution can also be assessed.

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