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Virtual testing environment tools for railway vehicle certification

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This paper describes work carried out in the work package 6 of the European project DynoTRAIN aiming at investigating uncertainties with respect to track and running conditions which have a bearing on the simulated behaviour of railway vehicle. Methodologies and frameworks for using virtual simulation and statistical tools as a mean to reduce both cost and time necessary for the certification of new or modified railway vehicles have been proposed. In particular the project developed a Virtual Test Track (EU VTT) toolkit capable of generating series of test tracks based on measurement for vehicle virtual testing using computer simulation models and capable of handling of output results automatically. The toolkit is compliant with prEN14363:2013. This has been used in the project as an experimental tool to analyse cross-correlation between track data (input) and matching vehicle response (output) based on the recorded data of the project test train. This paper presents issues encountered in the process and suggests future development and potential use in the context of European cross-acceptance with benefits from both a manufacturer design development and a regulatory certification point of view.

Keywords: vehicle dynamics, vehicle certification, virtual test track, homologation.

1 INTRODUCTION

1.1 Background

The recent European project DynoTRAIN aimed at investigating how the use of virtual simulation and statistical tools can help reduce both cost and time necessary for the certification of new or modified railway vehicles. The project was composed of 7 Work Packages (WPs) which are referred to throughout this paper. The WPs were as follow: WP1 (measurement of track data and vehicle response), WP2 (Track

geometry quality), WP3 (Wheel-Rail contact geometry), WP4 (track loading limits related to network access), WP5 (vehicle model and validation), WP6 (Virtual certification) and WP7 (Regulatory acceptance).

This paper relates to the work achieved in WP6, specifically looking at the question of variability of both the vehicle and the track physical and environmental characteristics and their effect on the results of the certification process. In particular, it was interesting to answer the question as to whether or not simulation tools are as capable at representing and taking into account the complete source of input parameters variation as real physical on-track test, while maintaining an equivalent level of accuracy and certainty of achieved results.

In many other industrial fields such as the energy sector the process of ascertaining the performance, reliability and security of a system relies heavily on the combined measurement of subsystem or component performance and whole system simulation. However in the field of railway transportation, the industry still relies primarily on measurement and feedback analysis to achieve certification of a vehicle. The improvement of models validation and their accuracy, such as that achieved in DynoTRAIN WP5 [7], and the ever increasing computing power should however, allow a more extensive use of simulations also in the railway field. For the certification of railway vehicles, the expected benefits of simulation are multiple:

- shorter and lower cost associated with acceptance procedures,
- possibility of achieving virtual tests on a wider range of running conditions and set of vehicle configurations, especially around critical situations that are difficult to meet experimentally,
- improving the knowledge and objectivity of the system's behaviour.

However, if simulation is introduced in certification, it has to be very representative of the system's physical behaviour. The vehicle model has thus to be fully validated as per the methodology and guidelines proposed by WP5 and the simulations have to be based on a representative set of excitations as investigated in WP2. The system being highly non-linear, particularly for aspects related the wheel rail contact, a poor representation of the inputs can indeed lead to significant errors in the output. These

considerations are taken into account in the current experimental certification process by computing the certification criteria on a range of representative track sections spanning different running conditions (radius, cant deficiency) and track quality. The probabilistic post-treatment then accounts for a representative range of likely events.

1.2 Main output of work package 6

The main output of work package 6 has been to propose a methodology for introducing simulations in the certification process, allowing a representation of the dynamic response of the system at least as precise as the one given by the on-track measurement. In the first instance the project investigated the effect of variability in the vehicle parameters and its impact on the certification output, referring to prEN14363:2013 [2] and UIC518:2009 [3] norms assessment criteria. This is presented in a parallel joint paper from Funfschilling et al [10]. Secondly the project investigated the effect of track and other running conditions on the results of the certification. The outcome of which are presented in this paper, but first the testing requirements from the reference norms are reviewed with respect to how they are treated in vehicle dynamic simulations.

2 CURRENT REQUIREMENT FOR VEHICLE CERTIFICATION

2.1 On-track test requirement from prEN14363:2013 and UIC518:2009 leaflet

At the time of the project and writing this article, two main documents are used as reference in Europe for vehicle certification; they are the prEN14363:2013 code [2], superseding EN14363:2005 [1] and the UIC518:2009 leaflet [3]. Other regional specificities may apply and this was reviewed and reported within WP4. The part of WP6 work presented here mainly refers to the first documents, and the UIC leaflet is referred to when differences are noted. During the project, the changes to EN14363:2005 implemented in prEN14363:2013 have been included wherever possible. This latest revision of the document makes more reference to simulation in the certification process and simplifies some of the requirements for testing. prEN14363:2013 scope includes both stationary (rotational resistance, sway, track twist...) and the dynamic testing of vehicle under service condition. The work here is only

concerned with the on-track dynamic testing part. The dynamic testing aims to cover two essential aspects of vehicles characteristics: a) the higher frequency dynamic effect of vehicle in response to track input around its maximum operating speed or maximum cant deficiency covering aspect related to the safety and running stability and b) the effect of quasi-static forces in small and tight curves covering aspects related to track forces and safety criteria. To test the full spectrum and combinations for the above, four test zones are defined in [2] and they are summarised in section 2.1.1.

2.1.1 *Testing zones*

Four test zones have been defined in prEN14363:2013 aiming to fulfil the following objective:

- Zone 1 – straight track and very large radii: testing the vehicle in the areas of permissible speed to look for high dynamic forces and accelerations
- Zone 2 – large radius curves: testing the vehicle in the area of vehicle permissible speed and high cant deficiency to look for combined large dynamic and quasi-static forces and accelerations
- Zone 3 and zone 4 – small and very small radius curve respectively: testing the vehicle for large quasi-static forces and accelerations

Table 1 summarises all the requirements for testing in each of the four zones. The main requirements apply on the operating speed in zone 1 and 2 and the operating cant deficiency in all zones.

Measurement from a test within each zone are cut into a minimum number of ‘test sections’ of predefined length [70, 100 250 or 500m depending on speed] as summarised in Table 1 and within each of these, 50%^{ile} (median) and 0.15 or 99.85%^{ile} (absolute maximum) values are populated for each assessment values. These assessment values are listed in section 2.2.1 and based on the statistical distribution of this population; a statistical maximum value can be estimated and compared with the standard limit for acceptance. Virtual test is therefore required to comply with the same testing procedure.

2.1.2 *Track quality*

In each test zone, the track is cut into the required number of test sections. The vertical and lateral quality of the track is quantified by taking the standard deviation value across each section for vertical rail

deviation (highest of each rail) and lateral alignment (highest of each rail). Depending on the line speed, each track section can then be assigned to a specific track quality class as specified in prEN13848-6 [4]. The quality distribution of all selected track sections used for the certification assessment then needs to respect a set of values representative of typical European track, see Table 2 and Table 3. This is specified in [2] so that the 90th percentile of the test sections quality falls within the limits of track quality band D in both vertical and lateral direction. Virtual testing is required to comply with this.

2.1.3 Other track geometry testing variables

Other track geometry features that are relevant to the testing procedure relate to track twist and track gauge. Track twist although inherent to the cross level geometry used to produce the virtual test track environment, is not strictly used as a criteria for selection. Regarding the gauge, upper and lower limits for the mean gauge are specified in the norm and it is suggested that any virtual test track be checked for this compliance. All tracks produced during the project were found to be compliant and Figure 1 shows the upper, lower and average value for each test track in each zones.

2.1.4 Other testing variables

Other variables inherent to on-track test that are considered in [2] relate to wheel-rail conicity, radial steering index, rail inclination, wheel-rail friction and track stiffness.

The wheel-rail conicity and the radial steering index are directly derived from the wheel and rail profiles pairs used for simulation. Equivalent conicity ($\tan\gamma_e$) as defined in EN15302 [5] needs to be representative of in-service conicity for the type of vehicle and the region where the vehicle intends to run. Wheel profiles shall be used so that they have an equivalent conicity at least as high as that of a new wheel. Besides it shall be proven that the in-service, expected conicity shall not exceed by more than 50% or 0.05, whichever is the highest, the value encountered during testing. In WP6 it was suggested that measured rail profiles stemming from the same curves as those used in the virtual test track be used wherever possible, with one representative set of profiles per test section (high and low rail). If this data is not available, then it is suggested to use a representative measurement set from curves of similar radii.

Work carried out in WP3 has produced such a representative table based on the WP1 rail measurement campaign.

It was acknowledged during the project that the rail inclination in itself is not a valid requirement for testing and it does not need to be accounted for in simulation as an independent parameter. This is because the effective worn rail profiles in service tend to wear to match the shape of the wheels corresponding to the running traffic they see, irrespective of their original inclination.

The effect of track stiffness on the critical speed and track forces has been investigated in WP6 and it was shown that assuming rigid track leads to too severe estimate of the critical speed. Most vehicle dynamic software such as Vampire, Simpack or Vi-Rail include a resilient model of the type shown in Figure 2 accounting for the general flexibility of rails, fastening and sleeper/ballast interface and it is found to be essential in terms of accurately approximating the level of forces encountered during testing in the range of frequencies below 20Hz without the needs for more complex models such as those employed in WP4 [6]. Such a model is generally made of masses and spring-dashpot elements, representing the vertical and lateral degrees of freedom for the left and right rails suspended onto an additional mass also with vertical and lateral degrees of freedom. This third mass represents the movement of the sleeper associated with the compaction of the ballast layer and sub layer below.

2.2 Statistical post-treatment of certification results

2.2.1 Assessment criteria

During on-track test a number of instrumentation is used to monitor the vehicle's response in the time domain and data is normally sampled at 200Hz and then low pass filtered with a cut-off frequency of 20Hz as specified in EN14363:2013. The following channels are recorded to assess the performance in terms of running safety, track loading and ride characteristics:

- Assessment values of running safety:
 - Sum of the guiding force of a wheelset ΣY
 - Maximum sum of lateral axle box forces (Hmax).

- Quotient of guiding wheel force (Y/Q)
- Acceleration at the bogie in the lateral direction (\ddot{y}^+) or axle box acceleration for non-bogie vehicles (\ddot{y})
- Acceleration in the vehicle body in the vertical and lateral directions (\ddot{y}^*S, z''^*S)
- The moving rms (root mean square) for $\Sigma Y, \dot{y}$ and \dot{y}^+ are used for vehicle stability assessment
- Assessment values of track loading:
 - The lateral guiding (Y) and vertical wheel force (Q)
- Assessment values of ride characteristics:
 - Maximum and rms values of car body acceleration in the vertical and lateral direction (\ddot{y}^*, z''^*)

The cut-off frequency of 20Hz allows capturing all the vibration forces related to the vehicle modal characteristics which are typically in the range 0.5 to 2Hz for body modes and between 6-10 Hz for the bogie modes. Kinematic oscillation of the axles are also of interest as the typical Klingel wavelength oscillation falls below this cut-off frequency for typical wheel and rail conicities and can interact with the above mentioned frequencies.

2.2.2 *Statistical post-treatment*

After the above signals are acquired they are submitted to the following process:

- Measurement signal is filtered (low pass filter)
- Sliding mean is determined (if specified)
- Selected characteristic values of the frequency distribution are determined (0.15%, 50% and 99.85%) providing minimum, mean and maximum values for each test track section for each measurement. Rms values are also calculated as necessary.
- For each evaluation function the estimated maximum value of the sample $Y(PA)_{max}$ is calculated assuming a 1-dimensional or 2-dimensional statistical method. In the toolkit

developed in relation to the EU VTT only the 1-dimensional method is used, while the 2-dimensional methods has been investigated in another work package [11].

- The safety factor λ is calculated as the ratio between the limit value y_{lim} and the estimated maximum $Y(PA)_{max}$

The same process is applicable to the signals produced from the vehicle dynamic simulation.

3 PROPOSED VIRTUAL TESTING ENVIRONMENT

In order to replicate a testing environment which complies with the current standard requirements as described in the previous sections it was important to strictly apply the same rules in terms of testing vehicle speed, cant deficiency, and curve radii. In vehicle dynamic simulation it is often accepted that the wavelength range of input data be separated in terms of long and short wavelength, so that the track layout (straight, curves and transitions) are often defined independently from the short wavelength irregularity data (vertical, alignment, gauge and cross level). However it was felt that separating these two may lead to unrealistic or unrepresentative cases, which would not replicate accurately enough the real test conditions, such as the combined effect of the long wavelength curvature with cross level irregularities for example. This was confirmed by work carried out in WP2 showing that the correlation between track irregularity quality in the range 3-25m and vehicle response are only partially correlated (from 20% to 80% at most) and therefore combining all recorded signals is essential to cover most of the possible vehicle behaviour. The adopted approach was therefore to keep original features from real recorded track together. However, the next problem was then to decide on how to choose the sections of track that would be used for testing the vehicle in the virtual environment? Here again the approach was to stay as close as possible to real case and original track data, by selecting representative track portions from identified number of representative sections, selecting them based on their equivalent quality and so that the overall quality distribution of the resulting track matches the standard requirements as per [2]. The process of building the Virtual Test Track (VTT) is explained next.

3.1 The Virtual Test Track

3.1.1 Applicability and process

The VTT toolkit was built in the DynoTRAIN project with two main target applications in mind:

- Setting up a testing environment to replicate a test for which existing results exist for the purpose of vehicle model validation (this was carried out using WP1 measurement)
- Setting up a testing environment to carry out virtual certification of a new or modified vehicles (this is open to any input data available)

The process for building the VTT illustrated in Figure 3 includes a pre-processing phase of the input data, and a serial treatment of the track data that produces output test tracks in a format compatible with most commercial vehicle dynamics software. The processing is explained in section 3.1.3. Specific file types compatible with Vampire and Simpack have been coded as these software were used in the project. A log file is also produced that allows an automated post-treatment of the simulation results according to UIC518:2009 or prEN14363:2013 procedure.

3.1.2 Input data

DynoTRAIN collected representative track data into a database submitted from a large number of European railway networks, dividing them into speed categories matching those defined in [4]. The same applied to the data generated from the recording of the WP1 test train. A VTT is therefore produced only for a specific track category based on its speed range. The user therefore has to specify the target speed for which the VTT has to be produced and accordingly load the correct track data from the database. All data from both WP1 and WP2 database have been decoloured using the filtering process as specified by the WP2 project group. Additionally the pre-processor for WP1 data was implemented with a check on the availability of concurrent measurement from specific vehicles of the measurement train, so that a produced VTT could be used against a specific vehicle for model validation or other investigation. Figure 4 show an example of the WP1 pre-processing window highlighting the option to select country of the original measurement to be included in the search, the option to select track section with corresponding

vehicle measurements, narrowing down the search to match a more specific linespeed range, or vehicle recorded speed range, and also the minimum length of track to be considered for input. Plots allow a visualisation of the selected track data, with from top to bottom the vehicle speed (permissible, recorded and selected limited), the curvature, the cant and the irregularities (vertical, alignment and gauge). Once all options have been reviewed and suitability of input channels have been manually checked the program proceeds to the next step.

3.1.3 Track data treatment

The four main steps carried out by the VTT toolkit are:

- 1) Separation of the input data by type: straight track, curved track, transition curves, compound curves or reverse curves (see figure 5). The program additionally aims at recognising switches and crossings (S&C) and eliminates these from the process (specific cases with high rates of curvature change)
- 2) Calculation of the cant deficiency [12]. This is based on the curvature (one over the radius), the cross level (elevation of the high rail above the low rail in unit mm) and the speed of the vehicle (either recorded, fixed linespeed or fixed vehicle target speed, depending on user choice and target use of the VTT). Based on cant deficiency and curvature signal the track data is then separated according to testing zones: 1, 2, 3 or 4.

$$\mathbf{cant\ deficiency} = \left(\mathbf{11.82.V^2} \cdot \left| \frac{\mathbf{1}}{\mathbf{R}} \right| \right) - |\mathbf{cross\ level}| \quad (1)$$

where V is the speed in [km/h] and R is the curve radius in [meters]

- 3) For each test zones, the track is then further discretised into an optimised number of test sections according to the length specified [2] for a given test speed. Each track section is then assigned to a quality band based on the vertical and lateral signal standard deviation (after 3-25m band pass filtering) and maxima. Very large discrete defects are eliminated at this stage, as well as large standard deviation. Candidate sections are marked as possible test sections for the next stage. During the selection of candidate sections for the VTT the first entry and exit sections of any

curve or straight portion of track are eliminated from the candidates so that once the EU VTT is rebuilt from original data, the test results will never be taken from the section of track directly following or preceding a transition curve.

- 4) An algorithm is then applied which randomises the vector of candidate sections so that the selected ones are covering as much as possible the whole range of input data. The selection process takes place so that the cumulative quality function of the EU VTT respects the 90th percentile limit within quality band D. Figure 6 show the quality distribution of the submitted input track data according to bins corresponding to EN13848 quality band limits (top plot for horizontal level and alignment respectively on the left and right columns). The middle plots show the minimum number of sections required either side of the quality band D upper limit to conform to EN14363:2013, as well as the actual selected numbers of track sections to build the EU VTT. A margin defined by the user is used to augment the number of test sections included in the EU VTT in order to increase the representativeness of the EU VTT built. The bottom plots show the cumulative distribution of the original data (green-dashed line) and the selected EU VTT test sections (blue dots).

Figure 7 shows the process described above in point 1, 2, 3 and 4 in diagrammatic form. The final step is to reassemble all selected track test sections into the original order of the input track data.

3.1.4 Output

The output of the EU VTT program is a track data file which contains channels relevant for vehicle dynamic simulations: distance, linespeed, recorded vehicle speed (if the purpose is to match measurement results), left/right rail horizontal level, left/right rail alignment, curvature, gauge, and cross level. The default format is a Matlab file to allow easy manipulation of the data, but format ready for selected multibody dynamic software Vampire and Simpack have also been coded. These are generally separated into two file types, one containing the long wavelength (above 70m) and the other the short wavelength irregularities (1 to 70m). Figure 8 shows the typical plot that is produced together with the EU VTT data for checking that the output test track is appropriate, it includes the horizontal level, alignment and gauge

channels (top plot), the linespeed, recorded speed and calculated cant deficiency channels (middle plot) and the curvature and cross level channels as well as markers (red right pointers) indicating the location of the EU VTT test sections (bottom plot).

3.1.5 Other specific constraints on the assembly of EU VTT

During reassembly, the program searches for sections directly adjacent to either side of any selected test section so that the dynamic output of the vehicle at the entry and exit of any test section corresponds to the real track behaviour. In other terms there will always be three lengths of consecutive track section without artificial smoothing for any one length of test section in the middle. If two test sections are selected that follow one another then there will be 4 consecutive sections with two in the middle used for test results. If the EU VTT is built for target testing in zone 2, 3 or 4 (curves), then the transition in and out of the selected curve including the test section(s) are added to the VTT. After this the toolkit applies a cubic Hermitian smoothing function between all track data which are not consecutive in the original input data. Figure 9 shows an example configuration of selected test sections and additional running sections that are used to build a VTT.

3.2 Issues encountered while developing the EU VTT toolkit

3.2.1 Matching track quality simultaneously for vertical & lateral

The EU VTT toolkit is trying to achieve a good quality distribution for both the vertical and the lateral track geometry at the same time. It was however noted that when the input data is insufficient, it is difficult for both lateral and vertical distribution curves to meet the desired distribution. Table 4 lists all the VTTs produced, their test zones and their total number of sections. The vertical and lateral quality of all test sections are normalised with respect to the upper limit of quality band D and plotted against one another in Figure 10 (only selected ones). The best-fit 1st order linear regression function is calculated as well as the correlation coefficient r^2 . For some of the track the correlation coefficient is good and there is therefore a good correlation between the vertical and the lateral quality of the virtual track. However in a lot of cases the correlation is rather low or poor, meaning that it is difficult to achieve the same

requirement in terms of the quality of the cumulative distribution at the same time for the vertical and the lateral geometry. A slope with a value <1 means that the quality of the selected sections tends to be better in the vertical direction than the lateral (compared to the class D boundary).

3.2.2 *Obtaining a suitable minimum number of test sections*

Finding the minimum required number of test section was often proved to be difficult for the following reasons:

- Quality of the automatic detection of the track features (straight, transitions, compound curves, reverse curves and S&C...) leading to a proportion of input data being discarded; e.g too short curves, S&C, reversed curves, etc...
- Harsh conditions on the range of admissible cant deficiencies (I_{adm}) in zone 2, 3 and 4.
- Quality of measured data (signal drops, amplified signals, loss of accuracy with inertial system at slow speed).
- Lack of data for very high speed track (in this project)
- Lack of data for very tight curves (zone 4) because of scarcity of cases and also inertial measurement issues at slow speeds in very tight curves.

3.2.3 *Matching I_{adm} conditions in curves*

The conditions on the range of cant deficiencies to be tested for zone 2, 3 and 4 are often hard to meet depending on the input data used, and which speed is used to calculate the cant deficiency (linespeed, vehicle recorded or target speed). As an example the plots in Figure 11 show the difference in the calculated cant deficiency using the same input track, but either using a fixed target speed or the vehicle recorded speed for equation 1. In the first case (top plot) a lot of the curves have a mean cant deficiency within the upper and lower limits for zone 3 and 4, while in the second case (bottom plot) most of the same curves are below the lower limits as the recorded speed of the vehicle is lower than the target speed. The vehicle would not have achieved the required speed during the test in these curves.

3.2.4 *Finding representative sets of curves for testing in zone 2*

In zone 2, vehicles need to achieve both requirements of maximum admissible speed and high cant deficiency. Such conditions are sometime difficult to achieve in practice as acknowledged in the draft norm prEN14363:2013, quote: “Especially for high speed trains it is often not possible or necessary to include the combination of maximum speed and maximum cant deficiency in the test programme”. Figure 12 show the combination of curve radius and cant elevation necessary to achieve the required range of cant deficiency at a fixed maximum speed. The areas highlighted in red show the limitation implied by these requirements.

3.2.5 *Finding representative sets of curves for testing in zone 3 and 4*

There is a requirement for the average radius of all curves to comply with 500m (+/-50m) and 300m (-20/+50m) for zone 3 and zone 4 respectively. This rule was not implemented in VTT as the number of curves available to build the VTT was often limited. Figure 13 shows an analysis of the spread of radii and their mean values for all EU VTT generated for zone 3 and zone 4. Each section mean value is plotted and each colour corresponds to a different EU VTT. The mean radii per VTT are indicated by a dashed red line. For zone 4 the average always falls within the tolerance limits. For zone 3 the average quite often goes beyond the upper limit for three of the track generated (out of six).

3.3 **Recommended future development**

The following improvements are recommended to improve the functionality of the EU VTT toolkit in the future:

- Optimise the detection of the track features (curves, transitions, straight etc.) to increase the amount of input data which can be used.
- User input choice of radius cut off for zone 1 and zone 2 (higher than 600m).
- Optionally set all curves to have the same direction (multiply curvature signal by -1 in left hand side curves). This would allow making better use of input data (for example reverse curves have

been eliminated) and also potentially lead to an easier handling of the test track design layout which may be artificially define to better match with the test zone limits in zone 2, 3 and 4.

- Allow relaxation of the rules on cant deficiency limits, to allow selection of more track data.
- Create a robust and easy to use user graphical interface (GUI).

4 PROPOSED METHODOLOGY FOR VIRTUAL CERTIFICATION

A methodology was established within the project to introduce simulation in the certification process, the main objective of which is to allow a representation of the dynamic response of the system which is at least as precise as the one given by the measurement. Three objectives have been followed to achieve this goal:

- Determine the conditions in which the numerical simulation can be used to certify a vehicle.
- Propose a method to introduce the simulation in the certification process.
- Propose a way of post-processing the simulations to determine whether or not the vehicle is certified on the considered network.

The work was exclusively focused on extensions of certifications using virtual tools. This means that the proposed procedure can exclusively be performed on vehicle / track systems that are similar to another system for which on-track measurements are available. Moreover no new criterion is proposed: only criteria required by the current certification process are used.

4.1 Conditions in which virtual certification is possible

The use of simulation is only possible when the modelling can be extensively validated against on-track dynamic reactions both in the time domain and in the frequency domain. The procedure is described in UIC518:2009 appendix K, in prEN14363:2013 and output of WP5 [7-9].

Three cases have been envisaged in WP6 for the virtual certification process:

- Case 1 - Train running in other specific running conditions: The train has been certified for a network, and has to be certified for other specific running conditions on a network declared in

Notified National Technical Rules (declared NNTRs). The behaviour of the train in the new running condition is not too different from the behaviour observed during certification and this can be used as the validation base case for the model.

- Case 2 – All track conditions not met during the certification process: All test conditions were not met during the testing but the extreme required values have been covered to avoid inaccurate extrapolation. The tests are used to validate the model and the simulation can be used to complete the sample to the necessary size. Special attention has to be paid to ensure that the additional sample members from simulation fit to the characteristics of the tested part. If this is not the case this method should not be used.
- Case 3 – Slightly modified train: A train that has already been experimentally certified has been “slightly modified”. An important set of measurements are available to validate the modelling and the modifications only lead to small behavioural changes. If the suspensions have been changed, static tests of the new vehicle are required.

In these three cases, the behaviour of the simulated system has to be “similar” to the behaviour of the tested system. This similarity can be assumed if the train structure has not changed (no change of the type of suspension elements for example) and if the responses of the two systems are similar.

For illustration purposes the process in case 1 is shown Figure 14. This shows the sequential steps of building and validating the model against existing on-track tests; building two virtual test track corresponding to the old and the new running conditions; introducing the variability of coefficient of friction as well as representative rail profiles, verifying that each assessment criterion for the new running conditions are not diverging significantly from those predicted in the ‘old’ or existing running conditions (-30% to +20% suggested); and if appropriate check that the all assessment criterion comply with the limit values to allow certification.

5 CONCLUSION

The WP6 of DynoTRAIN proposed methodologies to increase the use of virtual simulation tools for the certification of the railway vehicles, which are required to take into account the numerous sources of uncertainties from vehicle, track, and running condition as well as testing does, to fully represent the possible behaviour of the vehicle during its service life.

This paper particularly focuses on the conditions relating to the track and how these shall be taken into account in a virtual environment for vehicle simulation. A methodology for setting up Virtual Test Tracks based on real measured from various network and line speed is explained. To do so, an EU VTT toolkit has been developed which is compliant with prEN14363:2013 requirements. Issues encountered have been exposed and ideas for future development of the tool suggested. The project has produced a useful library of Virtual Test Tracks which have been built based on the measurements carried out in the project and other collected track data. The application of the virtual certification process has been proposed for three specific cases of a vehicle already certified to be run on other specific running conditions, cases where all conditions have not been met in the certification process and the case of a slightly modified train.

6 RECOMMENDATIONS

Based on the work achieved in DynoTRAIN WP6 a number of recommendations towards achieving virtual certification can be made:

- It is recommended that such tools as those developed in WP6 and DynoTRAIN project may be used as standard for the industry in the future in order to provide appropriate virtual testing environment of railway vehicles design development and certification.
- Together with such tools, it could be a benefit to collect and maintain a standard track database such as that collected in DynoTRAIN which is representative of different countries and line categories. This would require maintenance over time as new regions and traffic types are added.

- It is also recommended to use representative pairs of measured rail profiles to achieve the virtual certification, more especially in curves. These have indeed a large impact on the certification criteria and here also a comprehensive representative database would be of benefit to the industry.
- A sensitivity analysis of the vehicle / track model is moreover encouraged to verify the design and robustness of the model but also to determine the elements that have to be carefully modelled [10].
- Improvements to the statistical accuracy of the assessment estimated maximum values could be achieved by using an increased number of virtual test track sections for each zone.

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Test zone	1	2	3	4
Definition	straight track and very large radius	large radius curves	small radius curves	very small radius curves
Radius	unspecified	unspecified	400m < R ≤ 600m	250m < R ≤ 400m
Cant deficiency	$l \leq 40\text{mm}$	$0.75 \times l_{adm} \leq l \leq 1.1 \times l_{adm}$	$0.75 \times l_{adm} \leq l \leq 1.1 \times l_{adm}$	$0.75 \times l_{adm} \leq l \leq 1.1 \times l_{adm}$
Speed	$V_{adm} \leq 100\text{km/h}$: $V = V_{adm} + 10\text{km/h}$ $100\text{km/h} < V_{adm} \leq 300\text{km/h}$: $V = 1.1 \times V_{adm}$ $V_{adm} > 300\text{km/h}$: $V = V_{adm} + 30\text{km/h}$	$V_{adm} \leq V \leq 1.1 \times V_{adm}$	$V \leq 1.1 \times V_{adm}$	$V \leq 1.1 \times V_{adm}$
Minimum number of sections	25			
Minimum total length	10km	5km	unspecified	unspecified
Section length	$V_{adm} \leq 160\text{km/h}$: 100m $160\text{km/h} < V_{adm} \leq 220\text{km/h}$: 250m $V_{adm} > 220\text{km/h}$: 500m		100m	70m

Table 1: EN14363:2005 requirement for test zone

Speed (in km/h)	Longitudinal level - Limit value of standard deviation (in mm)				
	Track quality class				
	A	B	C	D	E
$V \leq 80$	< 1.25	1.75	2.75	3.75	> 3.75
$80 < V \leq 120$	< 0.75	1.10	1.80	2.50	> 2.50
$120 < V \leq 160$	< 0.65	0.85	1.40	1.85	> 1.85
$160 < V \leq 230$	< 0.60	0.75	1.15	1.60	> 1.60
$230 < V \leq 300$	< 0.40	0.55	0.85	1.15	> 1.15
$V > 300$	N/A	N/A	N/A	N/A	N/A

Table 2: Longitudinal level limit value according to prEN13848-6

Speed (in km/h)	Alignment - Limit value of standard deviation (in mm)				
	Track quality class				
	A	B	C	D	E
$V \leq 80$	< 0.90	1.25	1.95	2.70	> 2.70
$80 < V \leq 120$	< 0.50	0.70	1.05	1.45	> 1.45
$120 < V \leq 160$	< 0.45	0.55	0.75	1.00	> 1.00
$160 < V \leq 230$	< 0.40	0.50	0.70	0.90	> 0.90
$230 < V \leq 300$	< 0.35	0.40	0.50	0.65	> 0.65
$V > 300$	N/A	N/A	N/A	N/A	N/A

Table 3: Alignment limit value according to prEN13848-6

	z1	z2	z3	z4	n_sections	slope	correlation
1		1			13	↓ 0.02	0.03
2			1		29	↓ 0.29	0.39
3				1	30	↘ 1.05	0.73
4	1	1			30	↘ 1.02	0.76
5			1	1	30	↓ 0.78	0.38
6			1		30	↘ 0.82	0.69
7	1				34	↘ 0.81	0.83
8	1				34	↘ 0.85	0.82
9	1				34	↑ 1.24	0.75
10	1				35	↘ 0.92	0.85
11			1		40	↘ 0.83	0.66
12	1				40	↘ 0.94	0.69
13			1	1	53	↓ 0.26	0.40
14			1	1	53	↓ 0.35	0.47
15	1	1			108	↘ 0.81	0.54
16	1	1			119	↓ 0.55	0.43
17	1	1			137	↘ 0.84	0.67
18	1	1			149	↓ 0.54	0.46

Table 4: Correlation analysis of the vertical and lateral quality in EU VTT

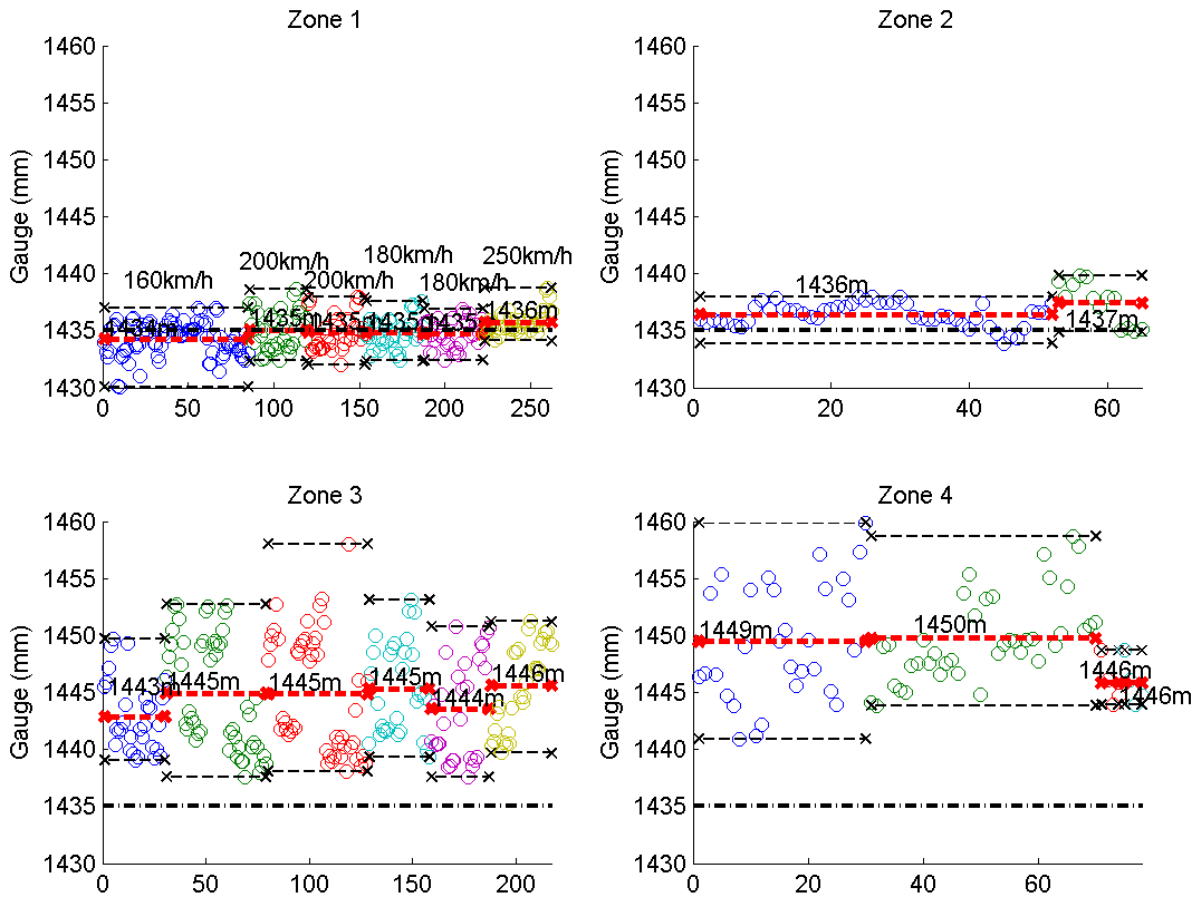


Figure 1: Compliance of Virtual Test Track for gauge spacing per specific test zone and test track.

Horizontal axis shows the test section number. Each colour set represent a different EU VTT.

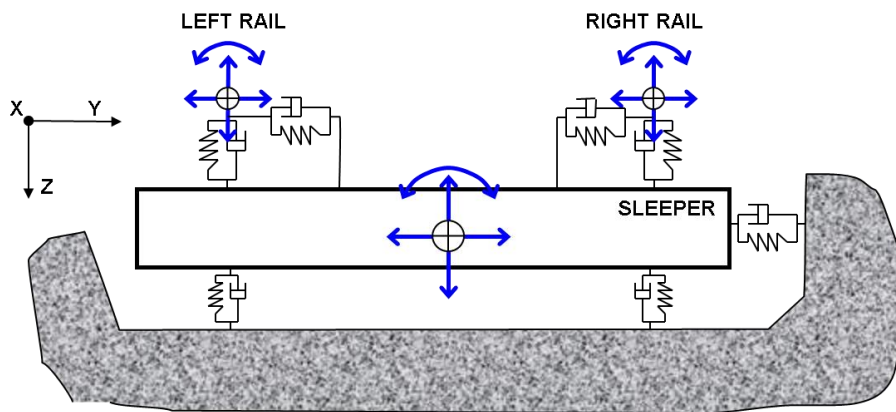


Figure 2: Example of a typical track model in vehicle dynamics software

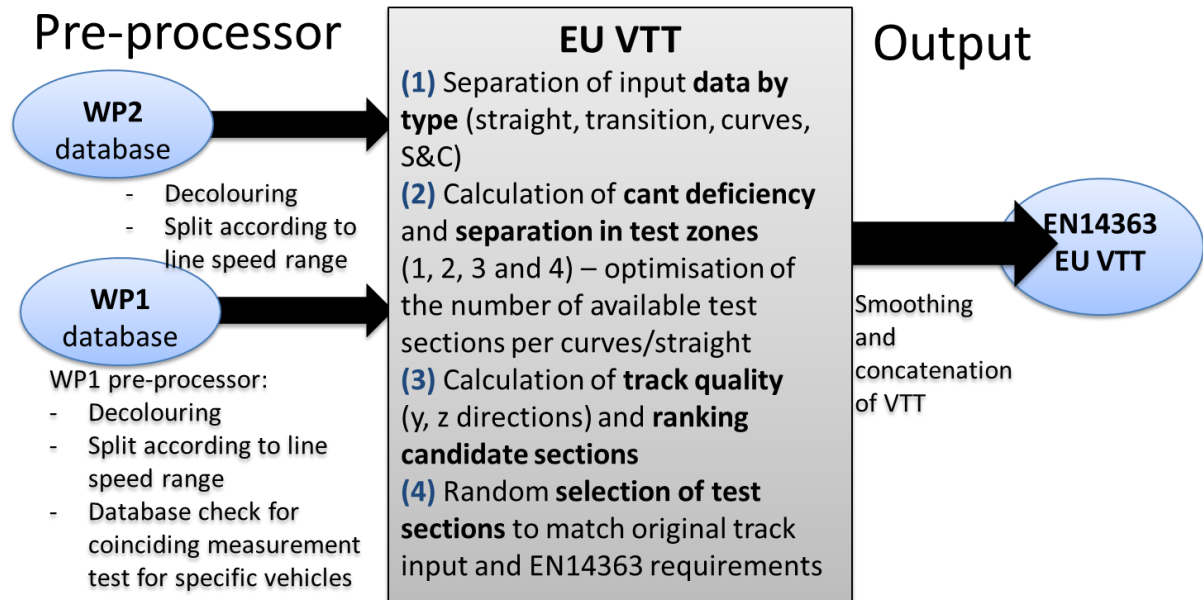


Figure 3: Virtual Test Track setup process. WP1 database consist of Dynotrain test train measurement and WP2 database is a collection of European track data obtained during the project directly from various infrastructure managers.

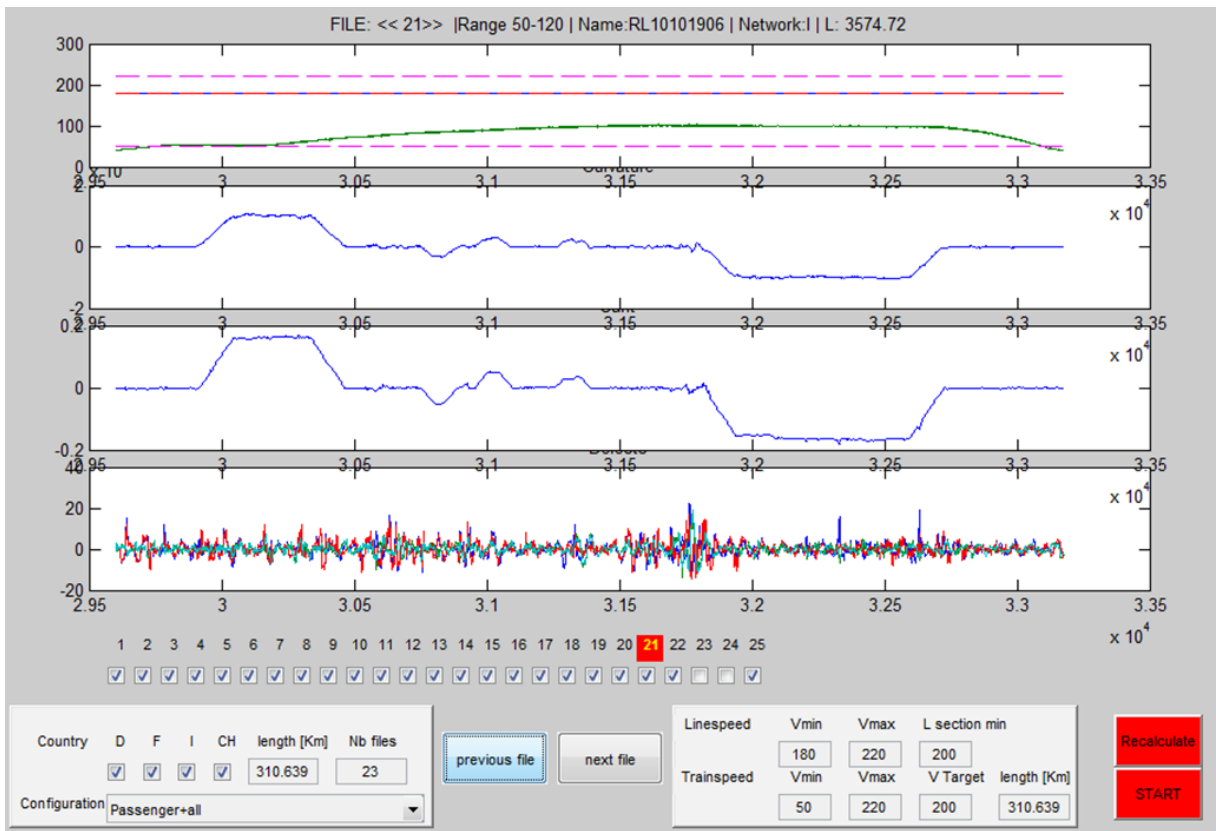


Figure 4: example of the pre-processing window options for WP1 database input

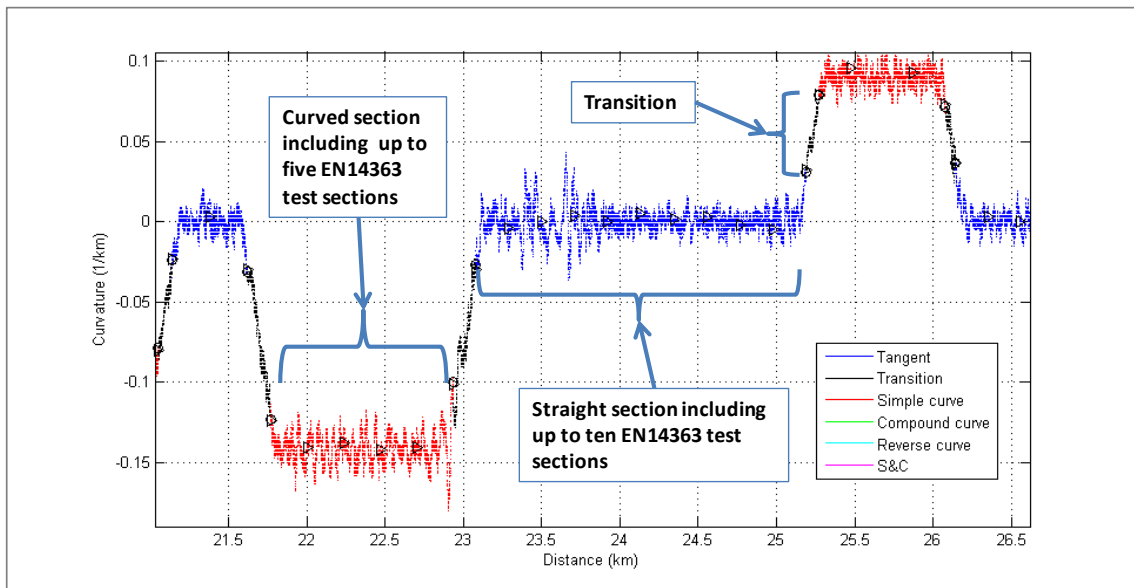


Figure 5: example of input data discretisation according to curve type (based on curvature signal)

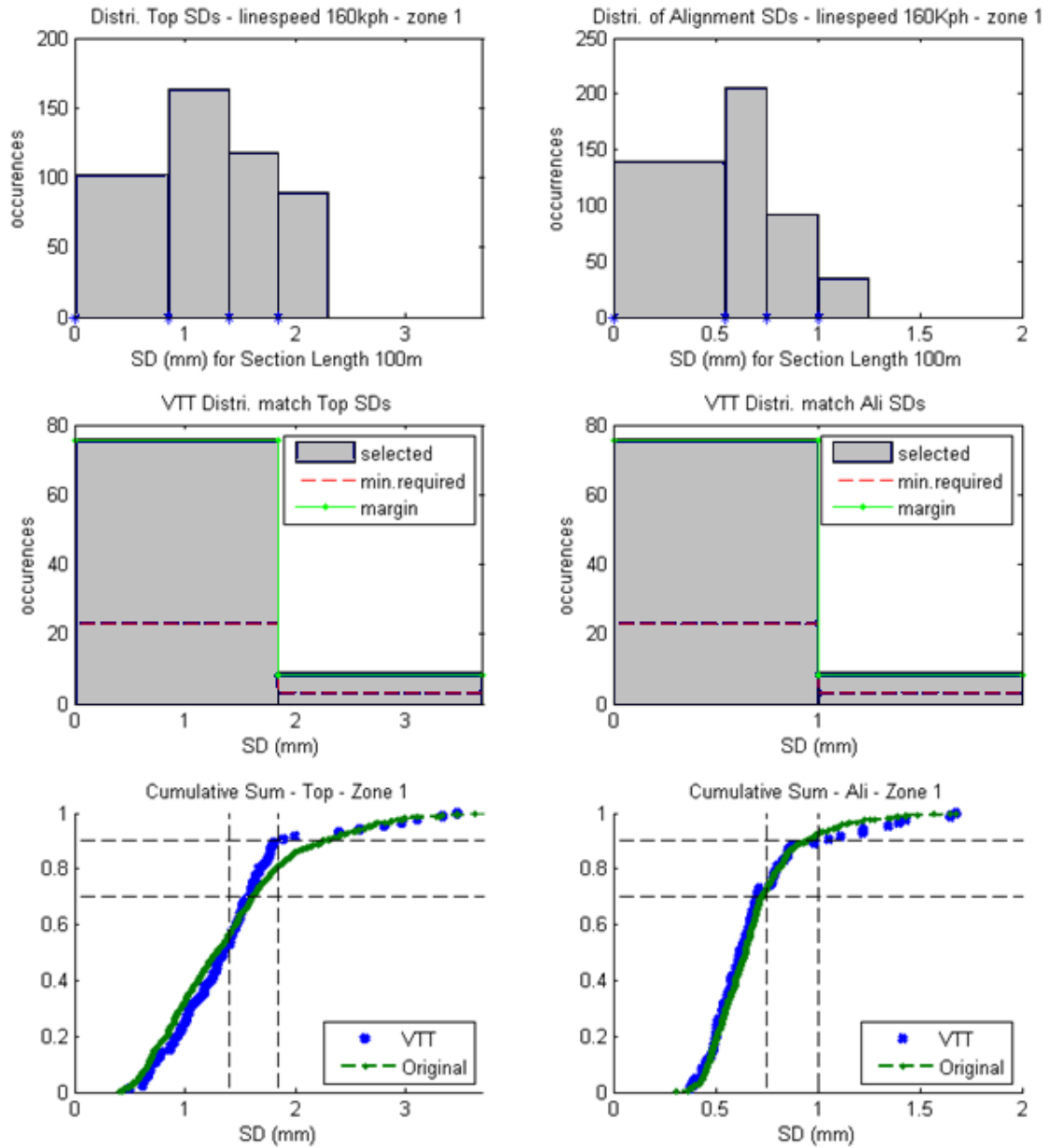


Figure 6: example of quality distribution of input track data and selected EU VTT sections

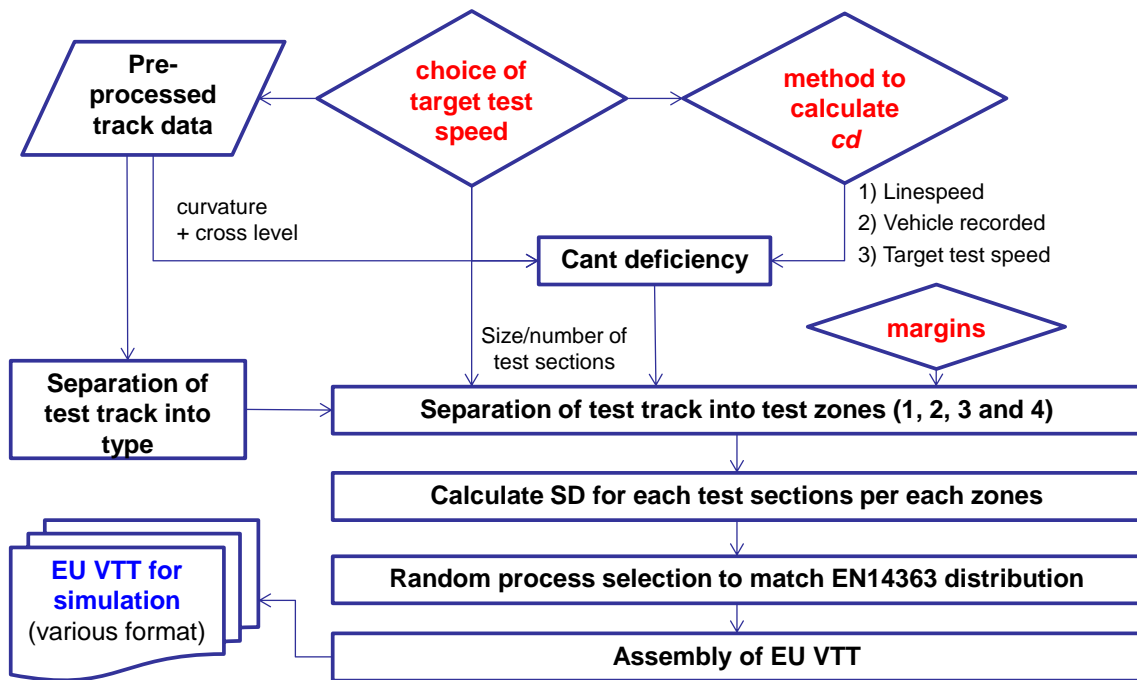


Figure 7: VTT toolkit internal process

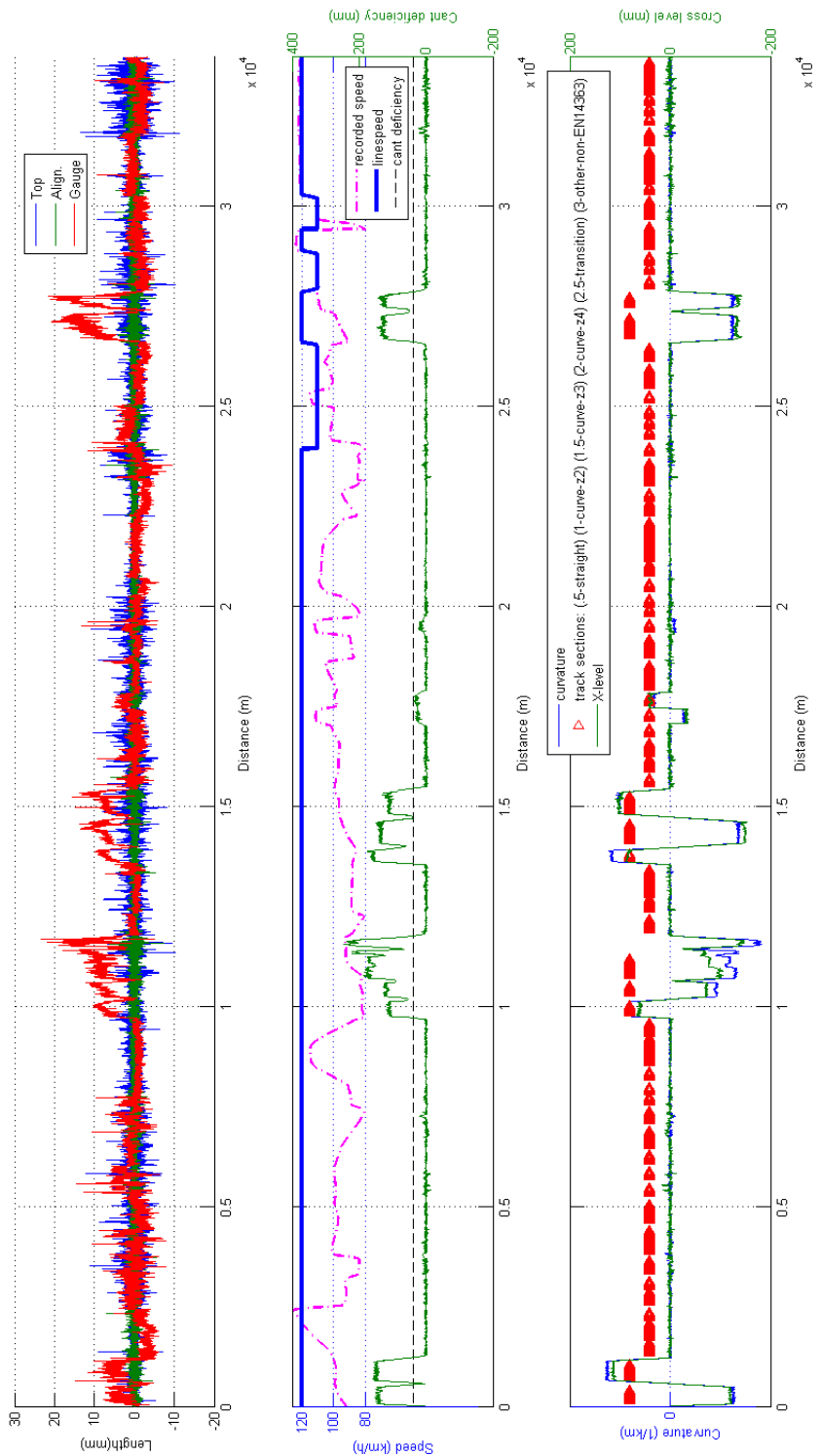


Figure 8: Example of output plot checking for EU VTT produced

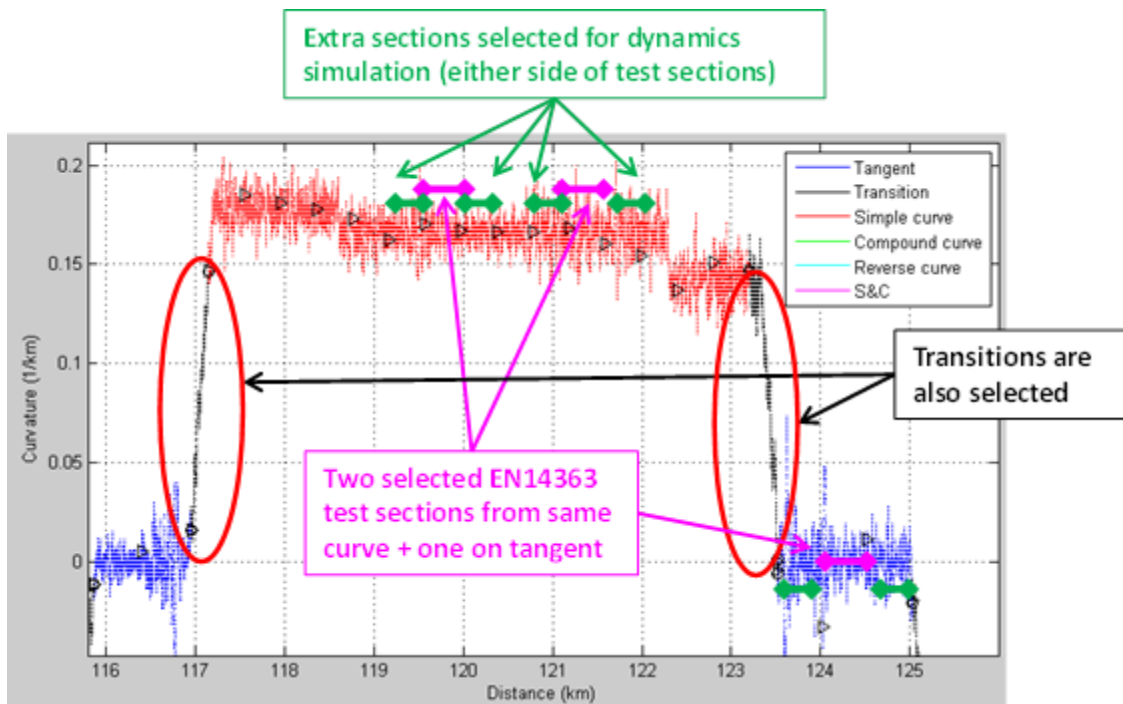


Figure 9: Example of the test and running sections used into an EU VTT assembly

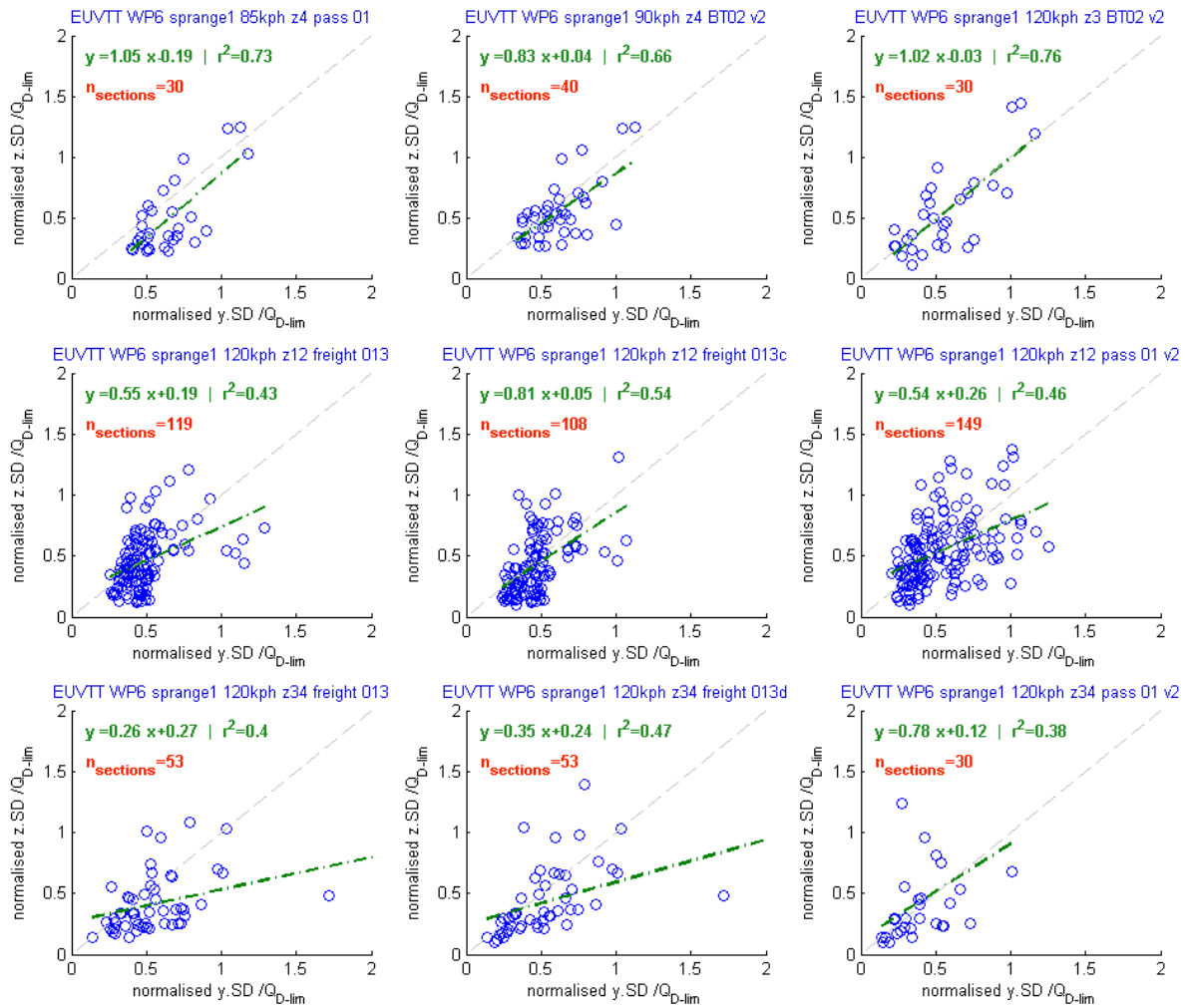


Figure 10: correlation plots between normalised vertical and lateral VTT quality

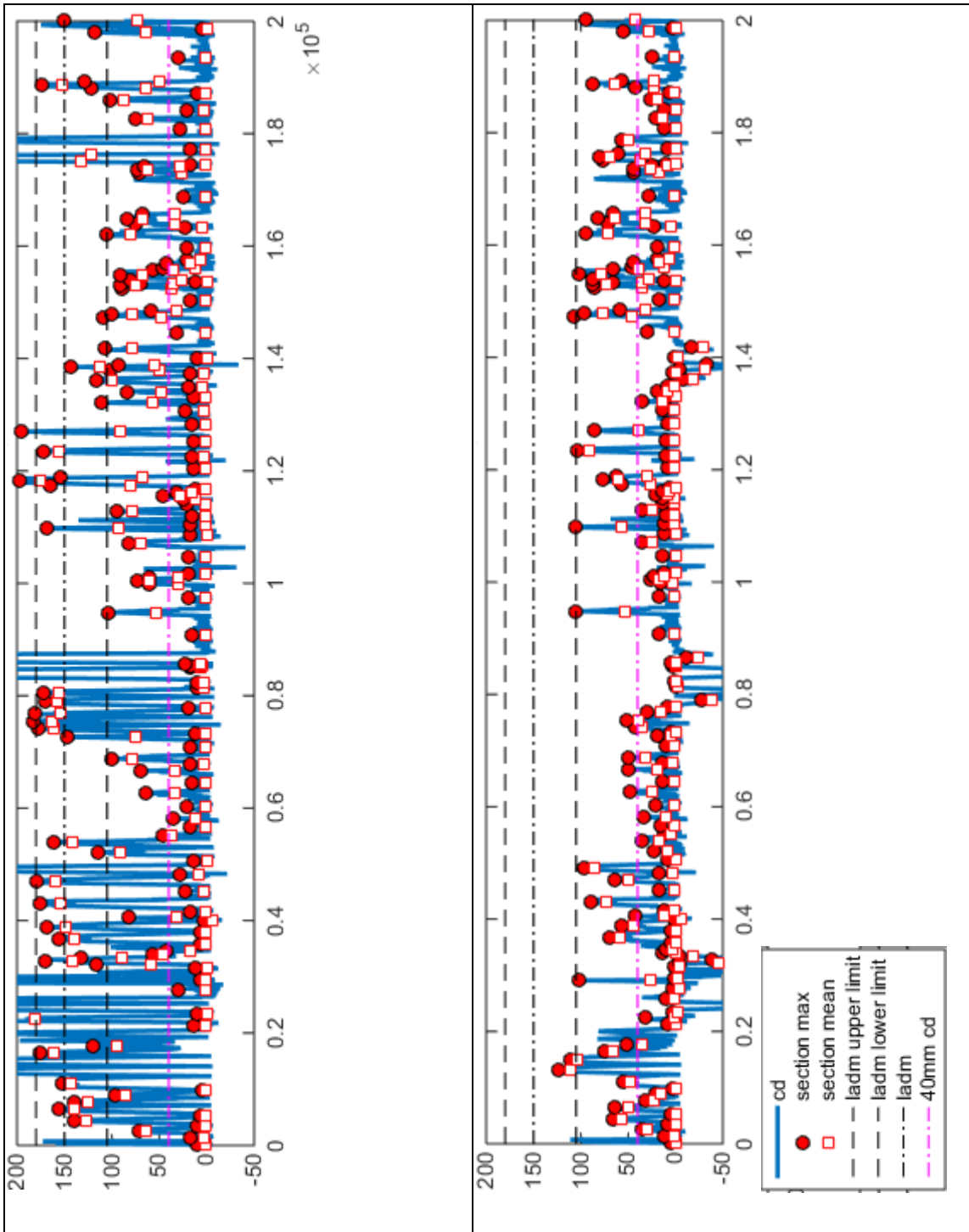


Figure 11: average and maximum section cant deficiency based on either target speed (left) or vehicle recorded speed (right), showing compliance or not with testing limit values

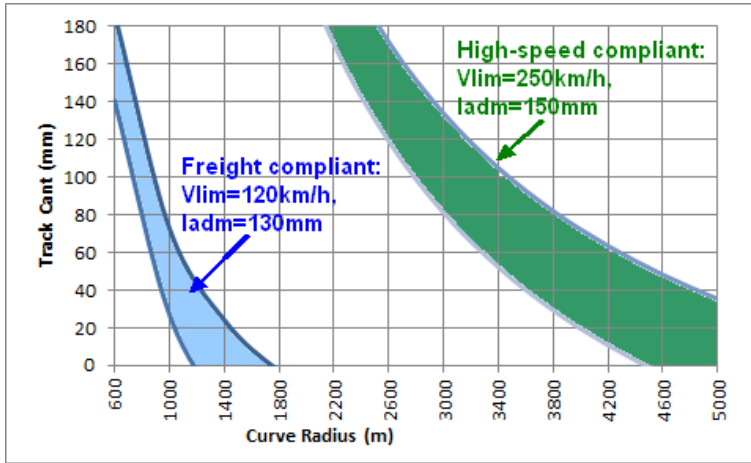


Figure 12: Envelope of curve radius and cant conditions allowing test in zone 2 taking into account the margin limit on cant deficiency ($0.75 \times l_{adm} < I < 1.1 \times l_{adm}$): for freight and high-speed vehicles

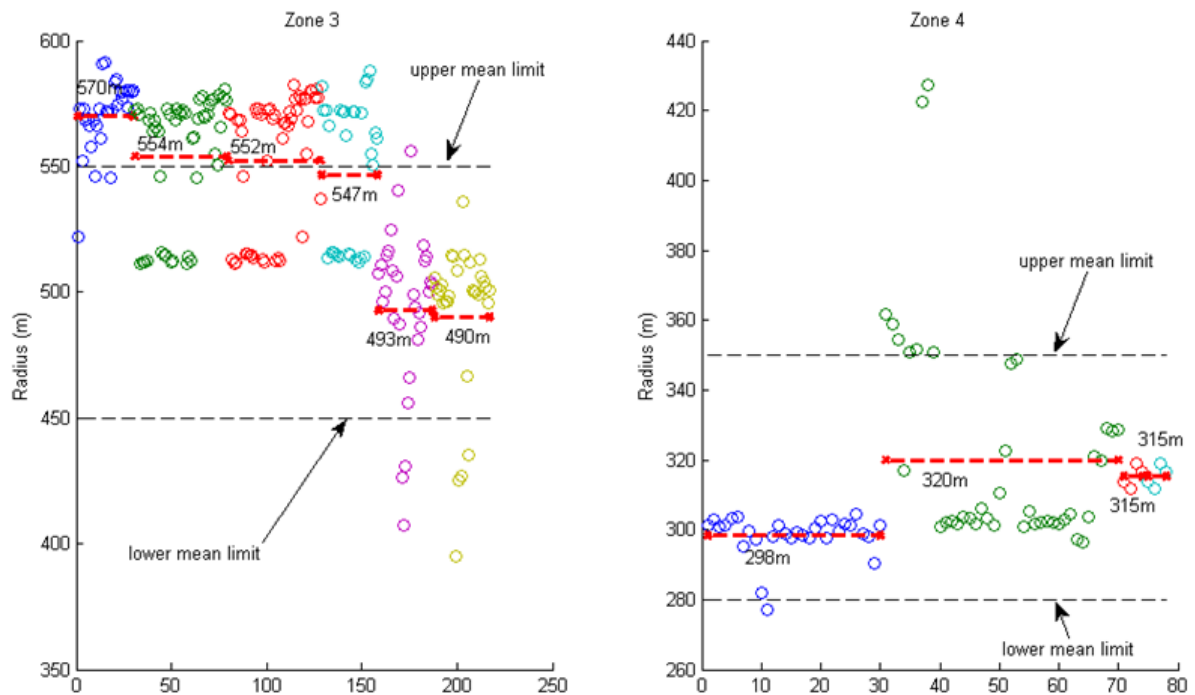
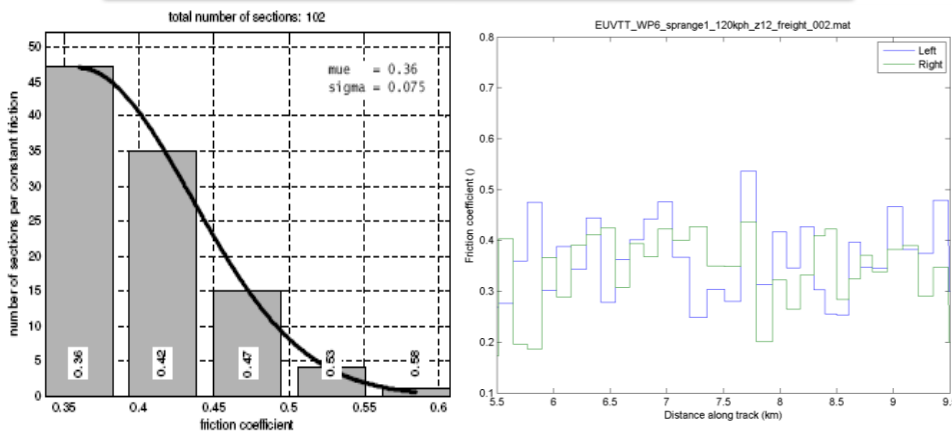
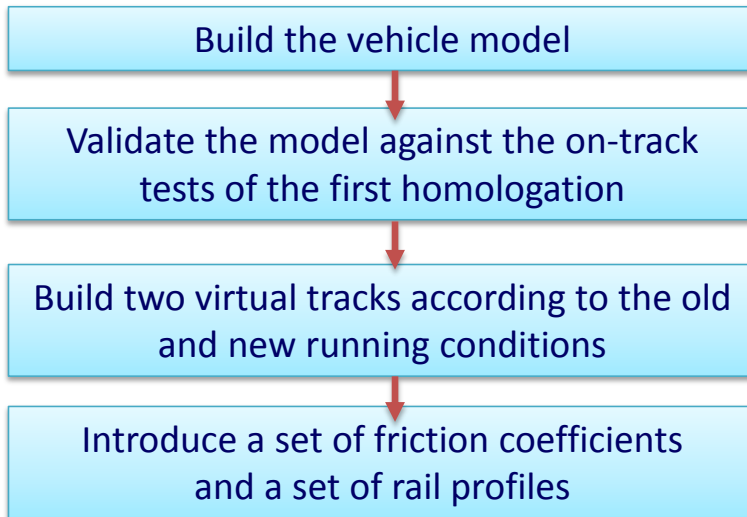


Figure 13: Mean radius analysis in zone 3 (left) and zone 4 (right) showing the spread of each section mean value (o) and average per test track (x--x).



For each criterion:

$$\langle y_{new} \rangle \in [0.7\langle y_{old} \rangle, 1.20\langle y_{old} \rangle]$$

$$\langle y_{new}^{estimated} \rangle \in [0.7\langle y_{old}^{estimated} \rangle, 1.20\langle y_{old}^{estimated} \rangle]$$

No

The use of simulation is not possible

Yes

Verify the certification criteria

For each criterion in each zone:

$$y_{new}^{estimated} < y^{limit}$$

No

Vehicle not certified

Yes

Vehicle certified on the new network

Figure 14: Case 1 - certification process of a vehicle running on other track conditions