

USING VEHICLE DYNAMIC RESPONSE TO CHALLENGE SET TRACK STANDARDS

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ABSTRACT

The risk of derailment has traditionally been managed by identifying local track defects where the measured track geometry exceeds some pre-specified limit value. Such limits are by their very nature conservative and usually only consider the track in isolation. They do not take into account the dynamic interaction between the vehicle and track.

The use of dynamic simulation tools provides the track engineer with the ability to target maintenance where it is most needed, by considering the complete interaction between vehicles and the track. It also allows identification of additional sites where, despite the track being within standard, there is a significant risk of derailment due to an interaction with the vehicle response. Such an approach has the potential to drive a step change in the way track maintenance standards are derived, resulting in:

- Optimised track maintenance to minimise derailment risk,
- Increased profit with a reduction in unnecessary maintenance,
- An improvement in overall ride quality.

This paper describes such an innovative approach, and provides an example of how analysis of vehicle track interaction can be used to set track geometry limits through the use of DeltaRail's VAMPIRE[®] software. The work, undertaken by DeltaRail, was commissioned by HTM (HTM Personenvervoer NV, with HTM coming from the former name Haagsche Tramweg Maatschappij) who operate a tram system around Den Haag (The Hague) in the Netherlands.

The project has involved the development of a tram model, validated against actual test results, and the use of measured track geometry data. This has allowed safety limits to be defined from which intervention and alert limits are derived.

INTRODUCTION

RandstadRail is a light rail network connecting the local tram and metro networks of The Hague, Zoetermeer and Rotterdam. Two former NS (Nederlands Spoorwegen) lines, known as the Zoetermeerlijn and Hofpleinlijn, were incorporated in the light rail network after being reconstructed. Some new tracks were also constructed. RandstadRail is exploited by HTM and RET, the public transport companies of The Hague and Rotterdam. Two different types of rolling stock are used: RET metro cars, to maintain the service between Rotterdam and the Hague and tram cars of the type Regio CITADIS for operation between the city centres of The Hague and Zoetermeer. The Regio CITADIS includes four bogies. The two end bogies are powered and have conventional wheelsets and the two centre bogies are low-floor trailer bogies using wheels on stub axles.

Within one month of the network being put into service in October 2006, nine derailments occurred and the approval for the service between The Hague and Zoetermeer was withdrawn by the railway inspection authority. It was almost a year before permission was given to resume this service. In the meantime intensive research was carried out by the different parties involved, to determine the cause of the derailments, as a basis for measures to be taken and to restore the confidence of both passengers and authorities. In particular the national safety council, the Onderzoeksraad Voor Veiligheid, was involved and published a public report [1] explaining how it was possible, for so many derailments to have occurred in such a short period.

Five minor derailments occurred at spring points. These derailments were due to inexperience of HTM personnel with this type of switch. One major derailment in a switch could be attributed to the locking mechanism being damaged during the construction of the network. Three derailments were due to heavily worn rails in a sharp curve. One major derailment however occurred at low speed in a transition curve after a canted 200 m curve (150mm cant). Also in this curve the rails appeared to be heavily worn. The derailment risk in this curve, located at Ternoot, was already recognized by HTM and studied before the line was put into service. The amount of design track twist in the transition curve (1:300) was considered too much. This study resulted in the recommendation to maintain a minimum speed of 50 km/h until the amount of cant and track twist could be reduced. Unfortunately the speed recommendation could not be satisfied in practice, due to the presence of a signal.

DeltaRail was asked to evaluate the track geometry of the line between The Hague and Zoetermeer and to develop a new standard for the track geometry. This standard should replace the provisional standard and should be based on the response of the rolling stock used, the Regio CITADIS tram, which is an articulated 70% low floor tram. This project covered a period of about nine months, in which a vehicle model was built and validated against measurements, and new limit values for track parameters were set on the basis of simulated vehicle response on measured track input. This paper describes this study.

In the following sections the work carried out by DeltaRail will be explained in more detail. A provisional track standard set by HTM will be presented and the general approach for the development of the new track standard will be discussed. After a description of development and validation of the VAMPIRE[®] model of the Regio CITADIS tram, the simulation results from this model will be presented. These results formed the basis for the new track standards.

RESEARCH PROGRAM

Evaluation of vehicle-track interaction by on-track testing

Shortly after the derailment in the 200 m curve at Ternoot and after the worn rails had been replaced, test runs were made with a CITADIS tram, equipped with video cameras. The purpose of these test runs was to check if wheel lift or flange climbing would occur and to observe the behaviour of the bogies in curves and switches. In addition to the monitoring of the wheel rail contact, the displacement of the primary suspension was measured. This made it possible to determine the amount of wheel unloading during curving. Later on these measurements were used to validate the vehicle model.

During the test runs in the curve at Ternoot, which took place under wet conditions, neither flange climbing nor wheel lift was observed. However, the guiding wheel of the leading motor bogie did show a considerable amount of wheel unloading, as was expected at low speeds. Figure 1 shows the primary suspension displacements of the leading axles of the first motor and trailer bogies before (red and blue lines) and after (orange and cyan lines) cant and twist had been reduced.

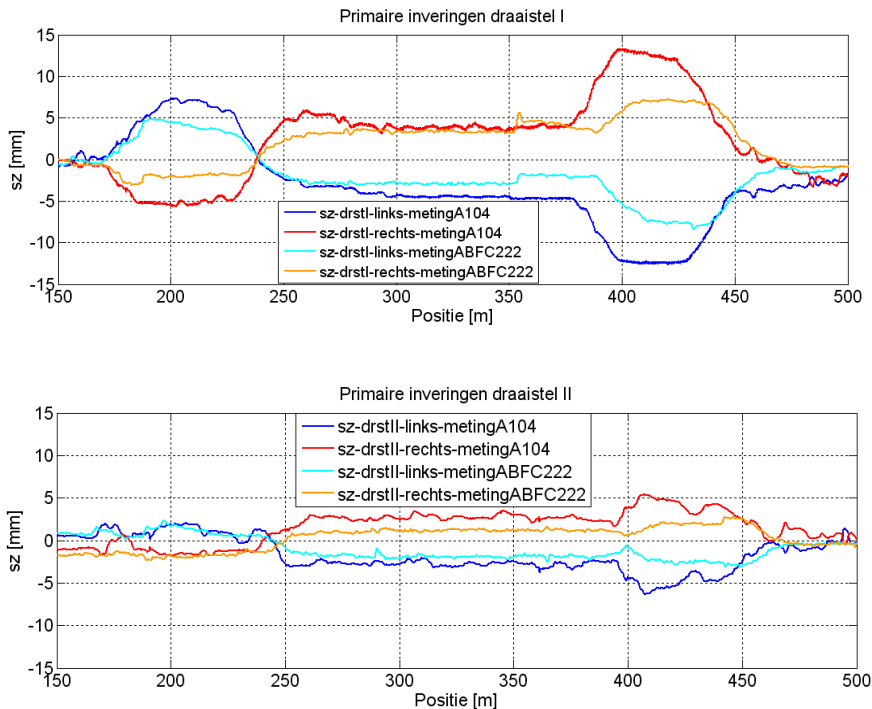


Figure 1 Effect of cant reduction on the primary suspension displacement of a wheelset passing the Ternoot curve at low speed. Upper: front wheelset of the leading motor bogie. Lower: front wheelset of the trailer bogie.

Because in the accident at Ternoot the leading wheel of the first trailer bogie had been derailed by flange climbing, it was expected that this wheel would show the most wheel unloading. Despite its higher suspension stiffness, the trailer bogie showed an unloading of about 21%, whereas the leading wheel of the motor bogie showed 36 % wheel unloading. Because the ratio of the horizontal and vertical wheel force Y/Q is decisive for flange climbing the conclusion was that the trailer bogie had developed a higher horizontal wheel force.

Apart from differences in the primary suspension system, there are several other reasons why in this particular case the trailer bogie could have developed higher lateral forces and therefore had a higher risk of derailment than the motor bogie:

- a) The trailer bogies under the low floor middle section of the tram are equipped with independently rotating wheels. These wheels do not have the ‘self-steering’ property of conventional railway wheelsets; lateral shift does not provoke longitudinal slip giving steering torques. Consequently the steering forces on these wheels are purely acting in the lateral direction and these can reach a higher level compared to conventional wheelsets.
- b) Traction forces on the driven wheels could have caused longitudinal slip, causing the lateral component of the resulting steering force to decrease.
- c) A higher rotational resistance of the trailer bogie could have caused a high guiding force on the leading wheel.

Simulations were recommended to reveal the precise reason why the less unloaded wheel had derailed, however priority was given to the development of the new track standard and to the validation of the HTM track recording tram, because the development of the new track standard would have to rely on the output of its measuring system.

Provisional track standards set for RandstadRail

After the derailments HTM defined a provisional standard for the track geometry based on the limit values of ProRail (the Netherlands ‘main-line’ infrastructure provider) for individual track parameters [2]. The corresponding ProRail limit values are based on the assessment of the track geometry at a single location by considering the worst response of a set of five vehicles on each track parameter separately. They do not take into account the combined influence of the different track parameters and do not consider the influence of successive track faults. The ProRail vehicle response is determined by filters which characterize the dynamic behaviour of the vehicles after linearization of their dynamic properties. The limit values are expressed as mid-chord versines for different chord lengths. There are two limit values defined for each track parameter: the safety limit value (VW) and a maintenance limit value (BW), which is set to 75% of the safety limit value.

To be sure that no new derailments would occur due to track geometry defects, the safety limit values were set by HTM to 75% of the ProRail maintenance limit values for the individual track parameters (Table 1, column HTM Provisional). HTM realized that this provisional standard was based on the behaviour of a mix of heavy rail vehicles, but considered it as sufficient until the new standard could be developed.

Table 1 HTM limit values for individual track parameters compared with the ProRail standard and EN14383.

Parameter	Chord length	ProRail (safety)		EN13848	HTM Provisional		HTM New Concept		HTM New Final	
		VW mm	BW mm	VW mm	VW mm	BW mm	VW mm	% lim response	VW mm	% lim response
Level mid chord	1 m	3	2,2		1,5	1,1				
	2 m						3	98	6.5	100□±□2
	6 m						20	98	24	100□±□2
	10m	24	18				28	98	29	100□±□2
	15m	30	22							
Alignment mid chord	1 m	4	3		2,0	1,5				
	2 m						3	90	3	100□±□2
	6 m						11	90	10	100□±□2
	9 m	18	13							
	10 m						19	90	13	100□±□2
Twist	2 m			12	10	8	12	89	23	100□±□2
	3 m	18	13							
	6 m			28.8	21	16	25	89	37	100□±□2
	10 m			35	27	22	27	89	36	100□±□2
	12 m	40	30							

General approach for the development of a new track geometry standard

The general approach in deriving a new track standard for RandstadRail is to develop a simulation model of the Regio CITADIS tram and to perform simulations with increasing track irregularities, until the safety limits for the vehicle reactions are reached. Looking back at the track irregularities then reveals the safety limit for the track parameters. The increasing track irregularities can be created by applying different scaling factors for their amplitudes.

During the initial part of the investigations the HTM track recording tram was not yet fully operational, but the opportunity arose to use a tamping machine for the measurements. This machine measures level and alignment as the versines of a chord of 12 m length. Apart from the fact that these track parameters had to be transformed into absolute geometry to make them useful for the simulations, the disadvantage of this approach was the relatively long sample interval of this machine of 1 m. This limited the range of

wavelengths that could be assessed. The advantage was, however, that the output could be used to validate the measuring system of the track recording tram. To ensure that the most restrictive geometry would be taken into account in the simulations, it was considered necessary to take into account at least 3 sample track sections of 1 km length each.

The new track standard was consequently developed in two stages. The first stage included the following actions:

- a) Development and validation of a VAMPIRE[®] model of the Regio CITADIS tram.
- b) Preparation of track input for the simulation of 3 track sections, derived from measurements with a tamping machine.
- c) Simulations with increasing scaling factors, equal for all track parameters, and assessment of the vehicle response.
- d) Definitions of limit values for individual track parameters.

In the second stage, which started when the track recording tram was fully operational and evaluated, the following actions were added:

- e) Selection of 4 additional track sections, measured by the HTM track recording tram
- f) Simulations with increasing scaling factors, different for each track parameter and assessment of the vehicle response.
- g) Definition of limit values for combinations of track parameters.

DEVELOPMENT AND VALIDATION OF THE VAMPIRE[®] MODEL

Development of the VAMPIRE[®] model

A simulation model of the Regio CITADIS tram was produced using VAMPIRE[®], DeltaRail's railway vehicle dynamics software package. In this type of model the vehicle is represented by a number of mass and wheelset elements which have mass and inertia properties, joined by mass-less suspension elements. The individual wheels and stub axles of the trailer bogies were straightforward to include in the model, as the axleboxes for each wheel pair are linked by a bar that constrains the wheels in yaw and roll. This means the wheels stub axles' behaviour is very close to a conventional axle with independently rotating wheels and they can be included in the model as such. A general view of the model is shown in Figure 2 below.

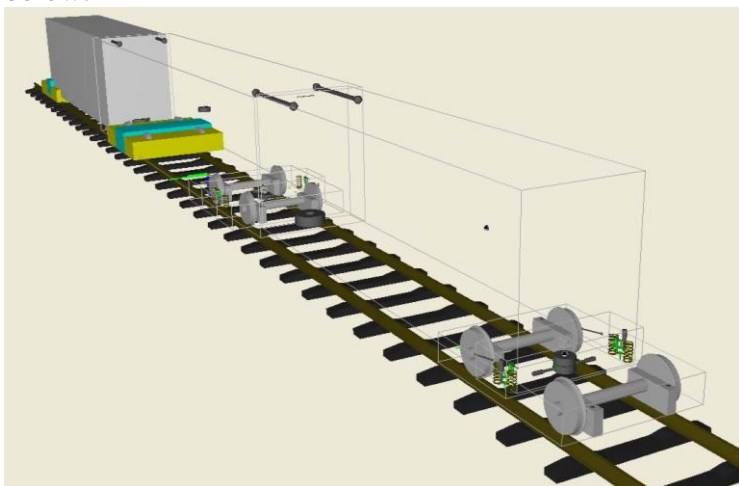


Figure 2 CITADIS Vehicle model

Validation of the VAMPIRE[®] model

Axleloads in the VAMPIRE[®] models were checked against parametric data supplied by DeltaRail BV and matched closely to them. Other validation work is described below.

Comparison with UIC518 test results

A validation exercise was carried out by simulating part of a UIC518 test of the tram. In this test the tram ran on a 300m radius curve at 80.3km/h (the maximum speed of the tram) with 100mm of installed cant, giving 1m/s^2 cant deficiency, effectively a sway test case. This case could be easily reproduced in VAMPIRE[®], giving quasi-static wheel loads on the curve that could be compared to results from the track test. Results from the VAMPIRE[®] simulations compared well to the test results, with maximum actual errors of 2.6kN.

Comparison with measured displacements of primary suspension

The track tests made at the Ternoot curve derailment site (described earlier) provided useful information for model validation. Measurements of track cant and gauge, rail profiles and suspension movements from a Regio CITADIS traversing the site were available (as shown in Figure 1). This allowed a simulation of the tram at the site to be produced in VAMPIRE[®].

Whilst the simulations did not reproduce the actual derailment, which was to be expected because of the comparatively limited input data available, it did allow comparison of suspension movements between test and model. An example is shown below in Figure 3 for the leading motor bogie (for the case before cant and twist were reduced). This can be compared to the test result shown in Figure 1. The pattern and size of suspension movements are well represented by the simulations.

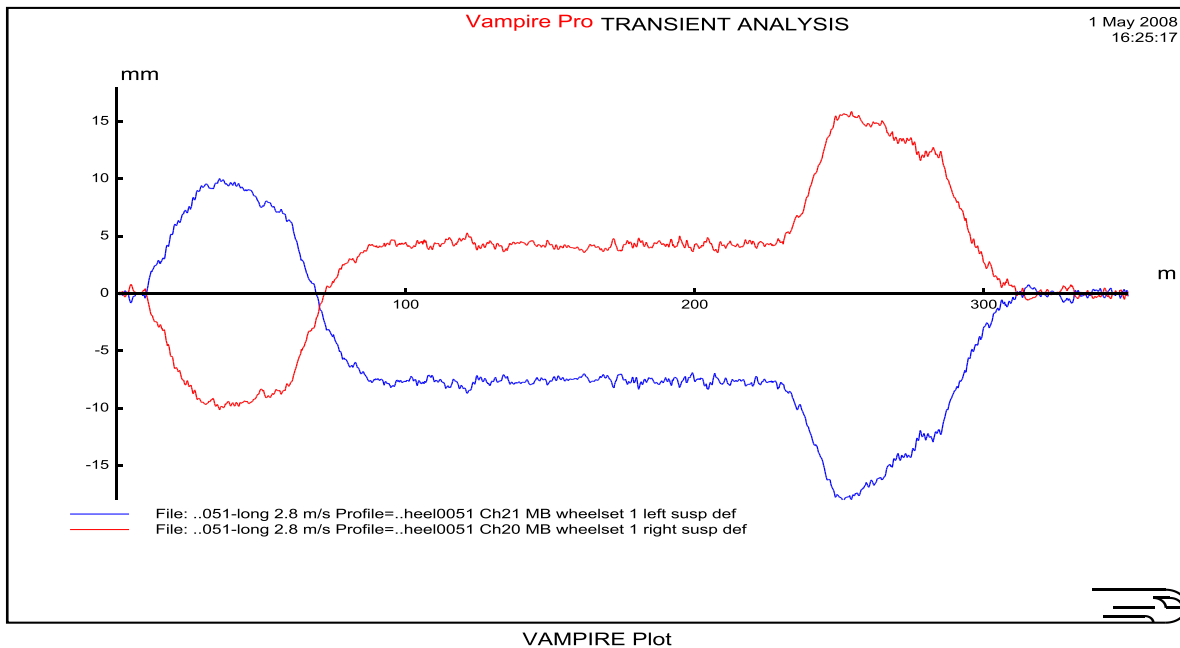


Figure 3 CITADIS motor bogie suspension movements, simulation

Comparison with bogie rotation tests

The CITADIS model was also validated against bogie rotation tests undertaken using a test rig produced by DeltaRail BV. Example results from the tests and the simulation, in terms of bogie rotation torques, are shown in Figure 4 below. The test result is shown in red, the results of the simulation in blue.

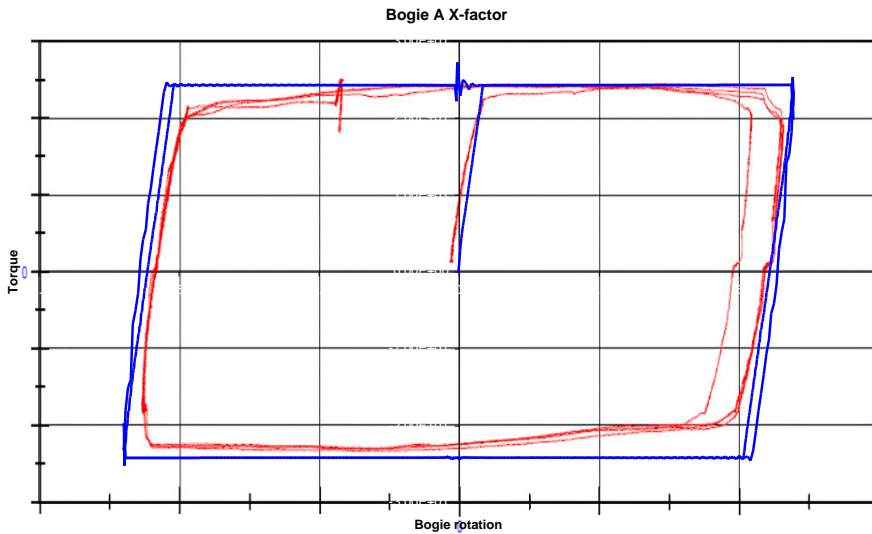
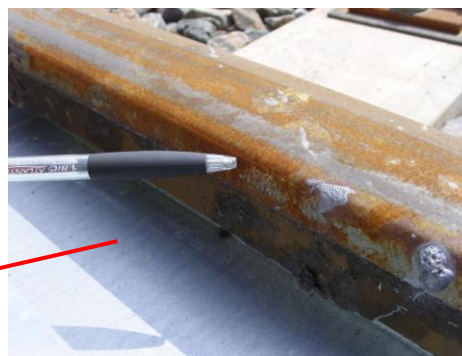


Figure 4 CITADIS bogie rotation, motor bogie A (leading end of tram)

Simulation of a derailment at the yard at Leidschendam

The derailment of a tram on 18 April 2008 in a curve at the yard at Leidschendam provided an opportunity for further validation of the simulation model. The derailment occurred at low speed in a 55m radius curve under dry conditions when the tram was leaving the yard (Figure 5). The rails at the derailment site were not worn, but the wheels of the tram had been re-profiled shortly before. This led to the conclusion that the effective coefficient of friction might have been rather high. The derailment was initiated by flange climbing of the leading wheel of the third bogie. This is a trailer bogie with independent wheels.



Derailment location on 2 June 2008

- 55 m radius curve
- Lubrication equipment installed after derailment
- Flange climbing still visible
- Rail not worn

Figure 5 Derailment site at Leidschendam.

To allow the derailment to be simulated in detail, both track geometry and rail profiles were measured. Figure 6 shows the track geometry plotted against position in the track together with the position of the tram at the moment of flange climbing.

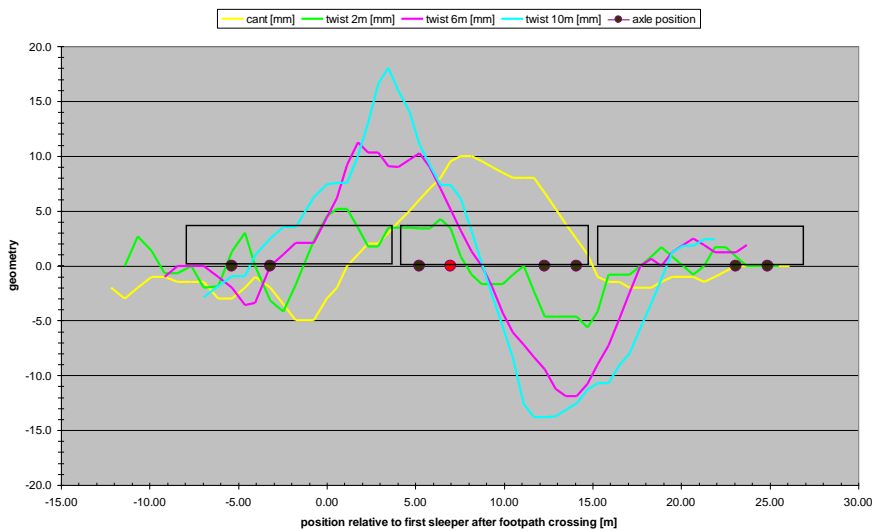


Figure 6 Cant and twist at the derailment site.

Due to the opposite signs of track twist for the middle (trailer) bogies it was concluded from this figure that track twist might have contributed to the derailment. Simulations however showed that track twist only played a minor role. The first simulations showed a tendency for the leading motor bogie to derail first. Application of a traction force on the wheels of this bogie changed this tendency towards the derailed bogie, but a derailment could still not be simulated. Further simulations with a very high friction coefficient of 0.55, decreasing the critical limit of Y/Q to 0.9, finally showed a high derailment risk (Figure 7).

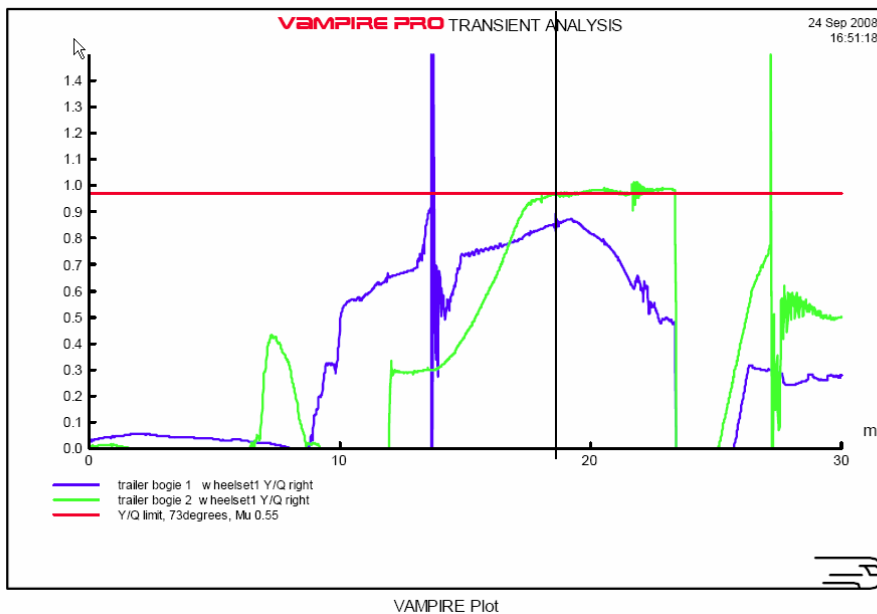


Figure 7 VAMPIRE® simulation result for Y/Q , showing high derailment risk for trailer bogie 2.

As said before, the high value of the friction coefficient could be justified by the newly profiled condition of the wheels and the very dry conditions during the actual derailment. A sensitivity study found that bogie rotational resistance influenced derailment risk. It was also noticed that the torsional stiffness of the tram played an important role. Therefore measuring torsional stiffness could have further improved the validation result.

DEVELOPMENT OF A NEW TRACK GEOMETRY STANDARD BASED ON VEHICLE RESPONSE

Track standard based on simulations with track sections measured by a tamping machine

The geometry of three track sections of 1 km length each, measured by a tamping machine, was chosen as the first input for the simulations used to set the track limits. Before this geometry could be used, it had to be split into separate inputs for track layout and track irregularities, because the track irregularities could then be scaled separately without altering the track layout.

The horizontal track layout was determined by calculating the 20m sliding mean of the alignment signal (versine) and by converting it into curvature. The vertical layout, in terms of cant and level, could be determined by taking the 20 m average from the cant signal and by deriving level from averaged cant in such a way that the track rotates around the inner rail of the curve.

The alignment irregularities were derived by calculating the difference between the measured signal and its 20m sliding mean and by transforming this difference into absolute geometry, by applying the inverse transfer function of the tamping machine. Because no signal for track gauge was available, track gauge was assumed to be constant. Later analysis showed that this was a reasonable assumption, because the track gauge appeared to be relatively wide and did not have much influence on the vehicle response.

In the first simulations the following input parameters were varied:

- Vehicle load: a fully loaded and an empty vehicle.
- Wheel profile: a new and a worn (measured) wheel profile.
- Speed: 10, 60, 80 and 90 km/h.
- Track: three track sections of 1 km length.
- Scaling factor for track irregularities: 0, 100, 150, 200, 250 and 300% (equal for all track geometry parameters).

So a of total 288 simulations were performed. 48 output parameters were considered for each simulation: the lateral and vertical carbody accelerations above the four bogies, the ratios Y/Q and $\Delta Q/Q$ for each wheel, and the total lateral track force ΣY for each axle. In order to assess these response parameters, their magnitudes were divided by their corresponding safety limits, as defined in EN 14363 (Table 2).

Table 2 Applied safety limits for vehicle reactions, based on EN14363.

Parameter	EN 14363	CITADIS empty		CITADIS laden		unit
		Motor bogie	Trailer bogie	Motor bogie	Trailer bogie	
ΣY_{\max}	$\leq (10 + 2Q_0/3)$	35.3	30.5	41.9	41.0	kN
Y/Q	≤ 0.8	0.8				-
dQ/Q	≤ 0.6	0.6				-
\ddot{y}_{qst}	≤ 1.5	1.5				m/s ²
\ddot{y}	$\leq 2.5 - 3.0$ *)	2.5 - 3.0				m/s ²
\ddot{z}	$\leq 2.5 - 3.0$ *)	2.5 - 3.0				m/s ²

*) 2.5 – comfort limit ; 3.0 – safety limit

The simulation results were assessed by a computer program that reads an arbitrary selection of results files, and generates an Excel table for each category of output. This table displays, for each speed considered, the extreme response values (minimum and maximum), their locations on the track, the

names of the corresponding results files (applied scaling factors included) and output parameters (channels). In table 3 an example of such a table is given for the output parameter Y/Q. By expressing the extreme response values as a percentage of their corresponding safety limit values, the results for different output parameters can easily be compared.

80067 Standardization track geometry RandstadRail								
Summary Vampire_storerresults.m								
Y/Q percentage of limit value (min and max) for track irregularities scaled to 300%								
date	21-04-2008							
speed	min.variant	min.chan.	min.value	min.pos.	max.variant	max.chan.	max.value	max.pos.
[km/h]			%	[m]			%	[m]
10	ZMR10-XL300Y300Z300-LW-10_f.csv'	MB1 Wheelset2 Y/Q right [No filter]'	27.7	800.0	ZMR10-XL300Y300Z300-TN-10_f.csv'	TB1 Wheelset1 Y/Q right [No filter]'	79.4	362.5
60	OHR1-XL300Y300Z300-LN-60_f.csv'	MB1 Wheelset2 Y/Q right [No filter]'	26.9	479.1	ZMR10-XL300Y300Z300-TW-60_f.csv'	MB1 Wheelset1 Y/Q right [No filter]'	86.8	426.8
80	OHR1-XL300Y300Z300-LW-80_f.csv'	TB2 Wheelset2 Y/Q right [No filter]'	44.4	488.8	ZMR10-XL300Y300Z300-TW-80_f.csv'	MB1 Wheelset1 Y/Q right [No filter]'	88.9	426.6
90	OHR1-XL300Y300Z300-LW-90_f.csv'	MB2 Wheelset2 Y/Q right [No filter]'	52.4	498.5	OHR1-XL300Y300Z300-LN-90_f.csv'	TB1 Wheelset1 Y/Q left [No filter]'	100.1	466.0

Table 3 Example of assessment program output for Y/Q.

The next step was to assess the track geometry at the positions indicated in the table. This was done by hand by displaying the amplified track irregularities and by estimating the value of the corresponding amplitudes.

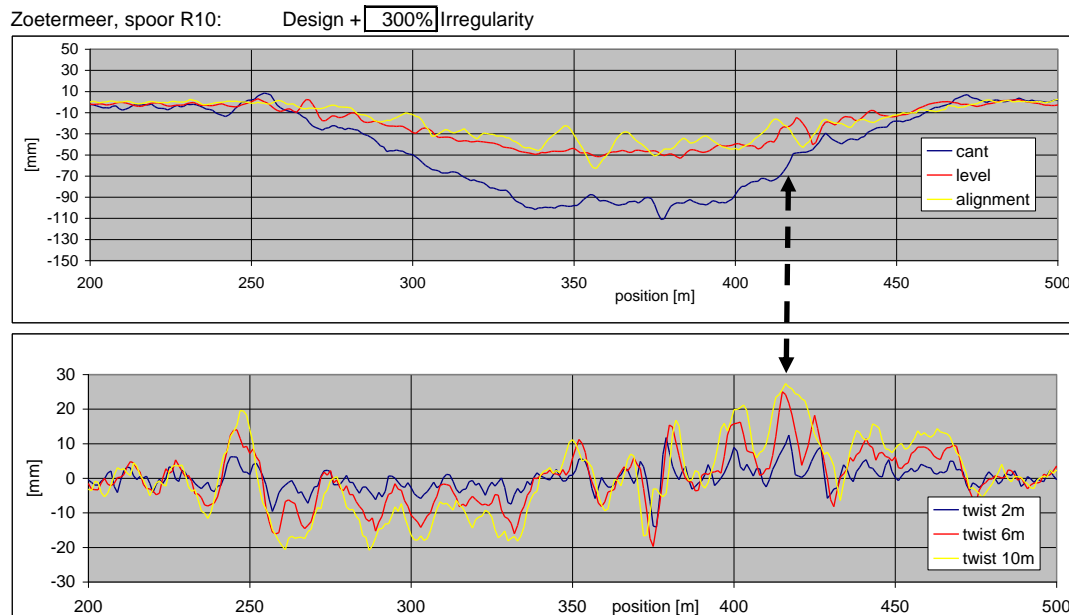


Figure 8 Assessment of track irregularities on track section ZMR10.

Figure 8 shows for instance the 300% amplified track irregularities for the track section highlighted in Table 3. From this figure the limit values for track twist over 2, 6 and 10 m can be fixed on 12, 25 and 27 mm respectively. As can be seen from this figure, track twist is not the only parameter responsible for the extreme value of Y/Q at position 426.6 m. Level and alignment also show a considerable variation around

this specific position and in fact the combination of parameters is responsible for the extreme value of Y/Q . However, in this case track twist can be considered as the dominant factor.

The same procedure was applied to examine the extreme values for the lateral track force and the body accelerations. It was found that level dominates the vertical accelerations and alignment appeared to be the dominant factor for both the lateral track force and lateral accelerations. Finally, the limit values could be fixed for the mid chord versines of level and alignment, based on the track values giving the extreme vehicle responses. The values found are included in table 1 in the HTM Concept column. As can be seen from this table the limit values derived using this method for track twist agree quite well with the HTM provisional values, based on the ProRail standard.

Evaluation of the HTM track recording tram

To evaluate the track geometry of the network, HTM equipped a service tram with an advanced optical measuring system. This track recording tram had been put into service shortly before RandstadRail was opened, but the measuring system had not been fully validated when the derailments occurred and the only track parameters considered were cant and twist. The derailments put a lot of pressure on the development and validation of the system.

The measuring system is an optical chord measurement system. It consists of a set of laser scanning cameras, which scan the profiles of the left and right rail in three different cross sections. The profiles of the outer cross sections provide the supports for a chord, which is used as reference for the relative positions (horizontal and vertical) of the rail profiles in the middle section. These positions are in fact the versines of the chord. The horizontal and vertical curvature of the track can be derived directly from the versines. The level and alignment of the left and right rail are also obtained from the versines by transforming them with the inverse transfer function of the chord measurement system.

In addition to the scanning devices, a rate gyro is used to determine the absolute roll angle of the carbody, to which the cameras are attached. The cant and twist can be determined by combining the roll angle with the output of the scanning cameras. An optional system to correct for the twist of the carbody could not be installed because of lack of free space under the carbody. The gauge is determined by comparing the lateral positions of the left and right rail profiles in one cross section.

Because the intention was to set up track limits based on simulations with measured track input, it was considered necessary to check the performance of the measuring system before simulations were made. Concerning gauge, cant and twist, the validity of the output could easily be checked by simple hand measurement equipment.

In order to check the output for level and alignment, comparison was made with the output of a tamping machine, which was equipped with a mechanical chord measuring system. The results of this comparison, shown in Figure 9 overleaf, gave enough confidence to start new simulations with measured track input. In parallel a project was started to assess the measuring system against the European standard EN13848-2 for track recording systems.

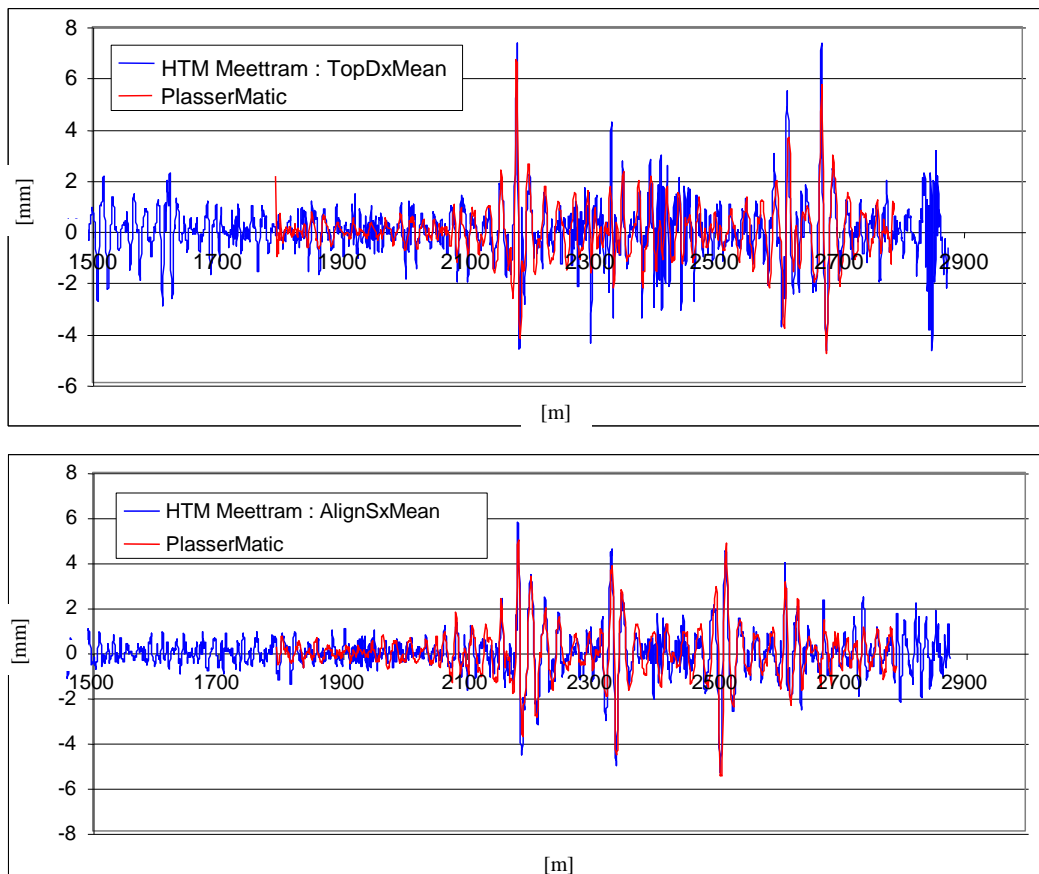


Figure 9 Comparison of measurement results of HTM track recording tram and maintenance machine.

Track standard based on simulations with track sections measured by the HTM track recording tram

In order to refine the assessment results, it was decided to perform simulations with different scaling factors for the individual track parameters and to consider more track sections, measured by the HTM track recording tram this time. In the earlier assessment of limits based on track measured by the tamper, it has already been noted that in fact a combination of track parameters was responsible for the extreme value of Y/Q found at position 426.6 m. Therefore the limit values in the HTM New Concept column of table 1 would not have an absolute meaning and could not be interpreted without reference to the combination of parameters that they belonged to.

To solve this problem, it was decided to look also for the limit values of the individual parameters, by applying the scaling factor on just one specific parameter and setting it to zero for the other parameters. The limit values found in this way are shown in the HTM New Final column of Table 1. It is remarkable that the limit values found for track twist are quite high compared to the values in the HTM New Concept column, whereas the values for level and alignment are more or less the same. The explanation for this is that the limit values for track twist also contain the track twist due to the track design. So when the cross level irregularities are scaled to zero, which was the case in examining level and alignment, there will still be a considerable amount of track twist apparent. Excluding cross-level will therefore not influence the limit values for level and alignment very much. When excluding level and alignment irregularities, however, cross-level (twist) can be raised considerably before the limit value is reached.

The next step was to examine the combined influence of twist and alignment in more detail. Simulations were performed with different scaling factors for cross-level and alignment irregularities, while the scaling factor for level was kept constant at 100%. These simulations were performed for speeds of 10, 40, 60 and 80 km/h. The scaling factors for cross-level and alignment were chosen so that the combination resulted in a 100% limit value for the most critical vehicle response parameter.

The assessment results for speeds up to 80 km/h and a chord length of 10 m are shown in Figure 10. The different colours refer to the track sections considered. The solid points indicate the critical combinations of twist and alignment for which Y/Q equals the limit value of 0.8. The open points refer to the critical combinations for which the most critical lateral body accelerations are equal to the safety limit of 3 m/s².

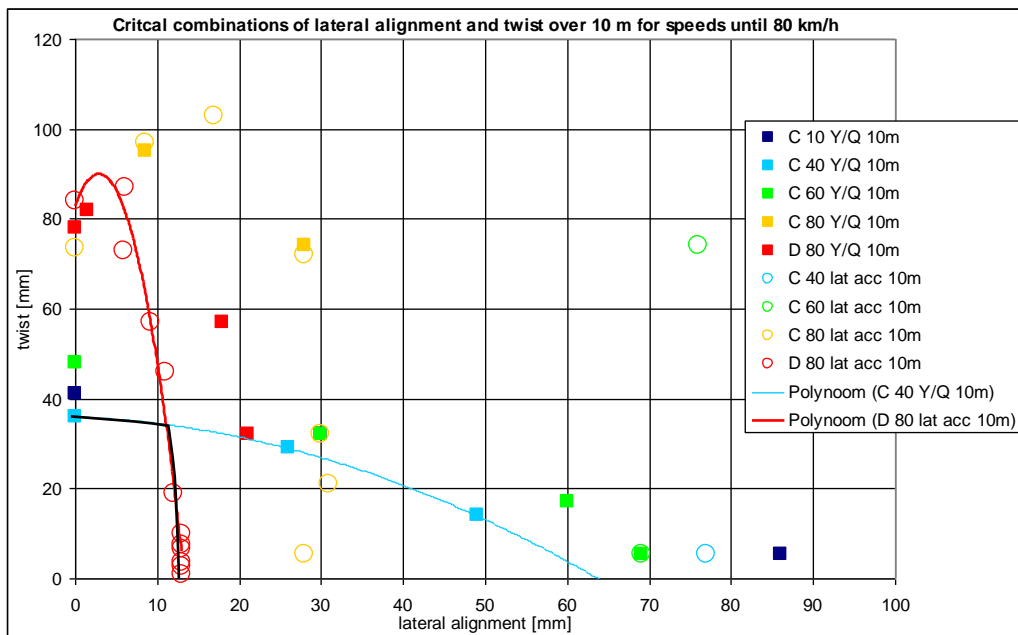


Figure 10 Critical combinations of alignment and twist over 10 m for speeds up to 80 km/h.

It can be seen from Figure 10 that for moderate values of track twist, lateral body acceleration (on track section D at 80 km/h) is the first limit exceeded as lateral alignment faults increase. The corresponding curve (in red) intersects the alignment axes at about 13 mm, the same value as presented in Table 1 in the HTM New Final column.

For higher values of twist and relative low speed, Y/Q is the first limit exceeded as twist increases, as can be seen from the curve for track section C at 40 km/h (in cyan). Also the point of intersection with the twist axis can be found in Table 1. The envelope of the two limiting curves, indicated by the black solid line, defines the critical limit for arbitrary combinations of twist and alignment. In a similar way the envelopes were drawn for chord lengths of 2 and 6 m and for speeds of up to 10, 40 and 60km/h. Also the influence of the rotational stiffness of the bogies on the critical limits was considered.

Finally the critical combinations were summarized in a look up table shown here as Table 4. The alignment values in this table are all mid chord versines. Where a slash is used to distinguish between two values, the first value refers to a bogie with design rotational resistance whereas the second value refers to bogies with an increased rotational resistance of about 2.5 times the designed value, representing a possible degraded condition.

Table 4 Limiting combinations of lateral alignment and track twist at different chord lengths for three ranges of maximum speed.

Critical combinations of lateral alignment and track twist in [mm] for speeds up to 40 km/h							
chord length 2 m		chord length 6 m		chord length 10 m		determining response	
alignment	twist	alignment	twist	alignment	twist	Y/Q	lat. acc.
0	23 / 9.1	0	37 / 16	0	36 / 17	x	
3.7 / 1.6	16 / 8.6	16	29 / 15	26 / 12	29 / 16	x	
8.2 / 7.7	0	48 / 37	0	64 / 58	0	x	

Critical combinations of lateral alignment and track twist in [mm] for speeds up to 60 km/h							
chord length 2 m		chord length 6 m		chord length 10 m		determining response	
alignment	twist	alignment	twist	alignment	twist	Y/Q	lat. acc.
0	23 / 9.1	0	37 / 16	0	36 / 17	x	
3.7 / 1.6	16 / 8.6	16	29 / 15	26 / 12	29 / 16	x	
8.2 / 7.7	0	48 / 37	0	64 / 58	0	x	

Critical combinations of lateral alignment and track twist in [mm] for speeds up to 80 km/h							
chord length 2 m		chord length 6 m		chord length 10 m		determining response	
alignment	twist	alignment	twist	alignment	twist	Y/Q	lat.acc./sumY
0	23 / 9	0	37 / 16	0	36 / 17	x	
3.7 / 2.8	16 / 7	7.7 / 9.5	34 / 15	12 / 12	34 / 16	x	x
3.8 / 2.9	0	9.8	0	13 / 13	0		x

When populating Table 4, it sometimes appeared to be difficult to convert critical vehicle response value unambiguously into a limit value for track geometry. For instance in the case of track twist it was not always clear how the different chord lengths contributed to the vehicle response. Also, the assessment of body accelerations was sometimes problematic. Because long wave track irregularities dominate the lateral body accelerations at higher speeds, it was concluded that alignment limit values for a chord length of 10 m are in fact more important at higher speeds than those for a chord length of 2 or even 6 m. It is difficult to express this in a single table.

Another disadvantage of using Table 4 is that the critical combinations of track parameters were found most commonly in transition curves. As long as no distinction is made between straight track and curves, the limit values found are much too restrictive for straight track.

For the reasons mentioned above, HTM was advised to assess the track geometry also by assessment of the calculated vehicle response, for instance by using VAMPIRE[®] and the methodology used in reference[3].

ADDITIONAL INVESTIGATIONS

Derailment safety at four critical locations

Following the derailment in the depot at Leidschendam discussed earlier, an assessment was undertaken of the network from Den Haag to Zoetermeer, over which the Regio CITADIS trams operate. Four sites were identified as potential locations of increased risk of derailment, due to their curvature, installed cant, or combination of the two. For each site measured track geometry data was converted into a VAMPIRE[®] compatible format to allow dynamic analysis of derailment risk and, at two of the four sites, rail profiles were also measured. The study considered both new and worn wheel profiles.

On the curve at Netkous-CS the measured profile from the high (left) rail exhibited noticeable sidewear, as can be seen in Figure 11 below.

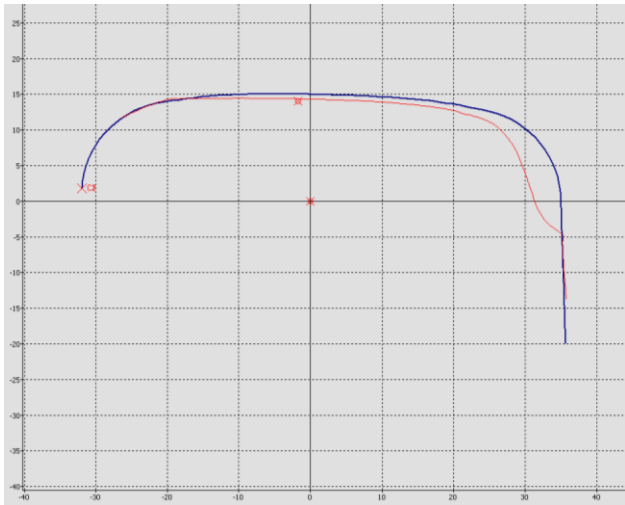


Figure 11 Measured high rail profile (red) superimposed upon design S49 rail (blue)

The pattern of wear indicates that on this curve, which is of 50 m radius, the tram runs in hard flange contact with the high rail. As a consequence the shape of the worn rail is a good match to that of the wheel flange, Figure 12, as would be expected.

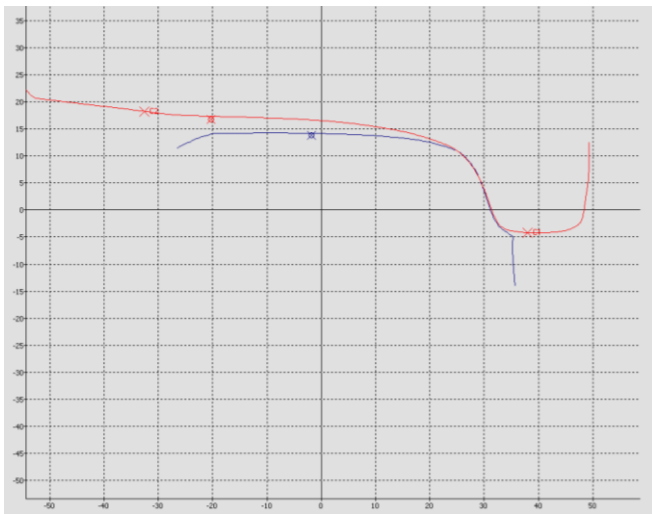


Figure 12 Wheel profile matched to the sideworn rail

The difference in rail profile from the design has the effect of changing the wheel rail contact conditions as the wheel runs into flange contact, however the maximum contact angle on the flange is little changed. The presence of the sideworn rail profile is therefore not expected to significantly increase the risk of flange climbing derailment. For derailment assessment a high value of wheel/rail friction ($\mu = 0.45$) was assumed at all wheel/rail contacts in order to represent worst-case conditions.

Simulation results

VAMPIRE[®] simulations were undertaken over each of the four critical track sites and the propensity to flange climbing derailment assessed by an analysis of the wheel unloading ($\Delta Q/Q$) and ratio of lateral to vertical force (Y/Q) at all wheels in the tram.

Appropriate derailment limits were as follows:-

- $\Delta Q/Q$ Limit = 0.6 Based upon the quasi-static wheel unloading limit used in torsion tests.
- Y/Q Limit = 1.1 Limit value for safety against flange climbing derailment derived from Nadal's equation assuming a 72 degree flange angle and a coefficient of friction of 0.45.

The HTM system operates in accordance with European Standard EN 14363 and this quotes two limiting values for Y/Q . A value of 0.8 is used for running safety on curves with radii greater than 250m and a value of 1.2 when testing for safety over track twist under quasi-static conditions, the latter value being derived from Nadal's equation.

In normal running, away from tight radius curves, vehicles would not be expected to generate high values of Y/Q unless there were large dynamic lateral forces, say from instability, or if the vertical load suddenly reduced, say from a track twist or cyclic wheel unloading. A limiting value for Y/Q of 0.8 is therefore appropriate in such situations, as is the requirement in EN 14363 to investigate instances where this value is exceeded in order to determine if this is due to vehicle or track (or combination of the two). On smaller radii curves the leading wheelset of a vehicle will run in flange contact with the high rail of the curve and quasi-static curving forces dominate. In such situations the limiting value for safety against flange climbing derailment, derived from Nadal's equation, is appropriate.

Given the curve radii at the different track sites it could be argued that the appropriate limit for Y/Q should be 0.8 at three of the sites (i.e. below the limit for derailment) whilst Nadal's limit should apply at the fourth, which is a 50 m radius curve.

For both $\Delta Q/Q$ and Y/Q the limit applies to data computed using a sliding mean over a 2 m length of track rather than to the raw time history data itself.

An examination of the simulation results showed that: -

- The unfiltered $\Delta Q/Q$ does not exceed 0.6 at any of the four track sites
- The unfiltered Y/Q does not exceed 0.8 at sites #1, #2 and #3
- The unfiltered Y/Q does not exceed 1.1 at site #4, Netkous-CS

Since the raw data does not exceed the limit values then nor will the filtered data.

Only at site #4, the track section Netkous-CS, did the predicted Y/Q values exceed 0.8. This is true even after the data is filtered with a 2m sliding mean, Figure 13, the largest value predicted being 0.86.

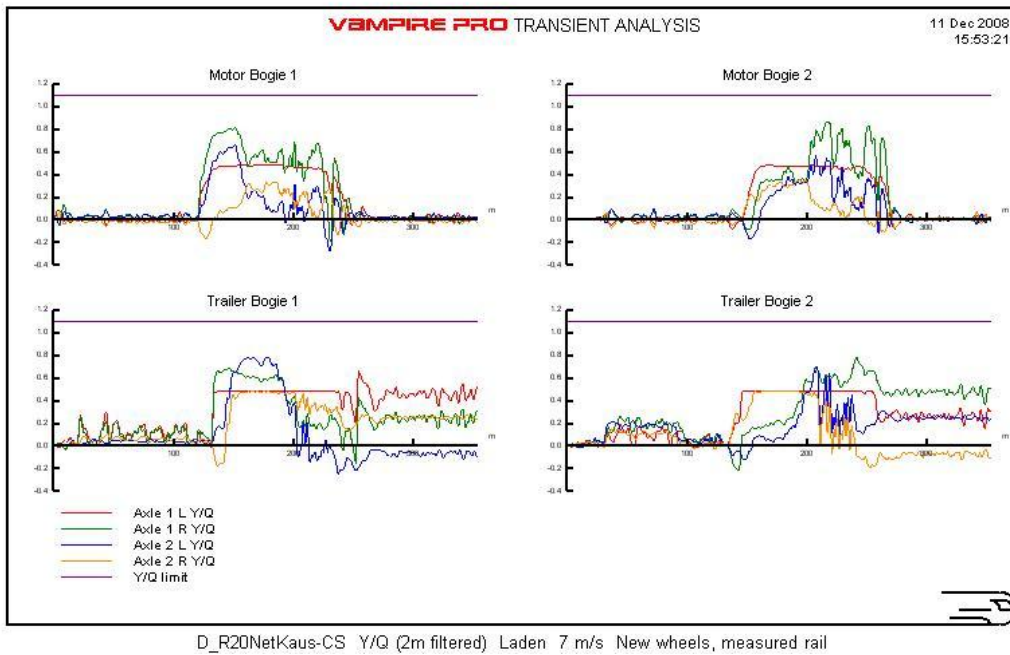


Figure 13 Filtered Y/Q Netkous-CS

This should not be unexpected given the 50 m radius curve at this site and the high coefficient of wheel/rail friction that has been assumed. The predicted Y/Q is still comfortably below the value at which flange climbing derailment might become an issue. For all four sites the derailment risk was found to be within acceptable limits.

Assessment of passenger comfort in curve transitions

One particular result of the assessment made of the network operated by the Regio CITADIS refers to a track with two apparently equal curved track sections. However, in the second track section cant and curvature are not tuned and no proper transition curve could be applied between the adjacent curves with radii of 300, 1200 and 300m, due to space restrictions. Figure 14 shows the lateral accelerations of the carbody when travelling at 80 km/h, the design speed for this track, together with the measured track geometry.

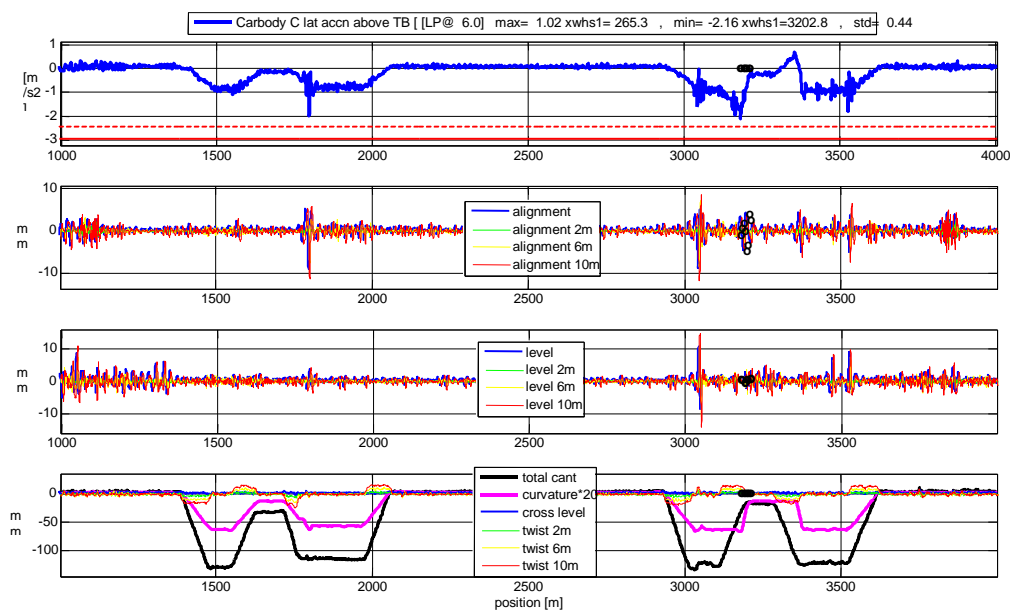


Figure 14 Lateral carbody acceleration related to the track geometry of two curved track sections.

Though no safety limits are exceeded, the lateral carbody acceleration changes sign rapidly in the second track section. In practice tram drivers complain about this situation. In order to quantify their complaints, the comfort index Pct, indicating the percentage of dissatisfied passengers according to EN12299, was evaluated for this section of track. Figure 15 shows the evaluation result for standing passengers.

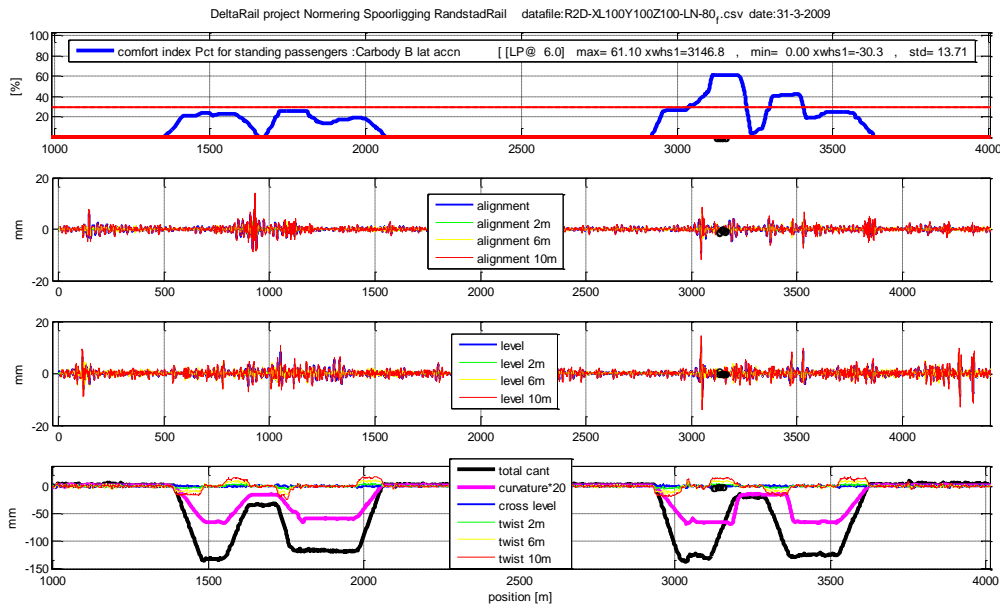


Figure 15 Percentage dissatisfied standing passengers at 80 km/h related to the track geometry of two curved track sections.

In the first track section Pct stays just below 30 %. In the second section however Pct for standing reaches values of 61 and 42%.

Table 5 shows how Pct on the second track section is influenced by the travelling speed. A speed reduction of 10 km/h reduces the amount of dissatisfied passengers significantly. When speed reduction is acceptable from an operational point of view, expensive adjustment of the track design could be avoided.

Table 5 Influence of travelling speed on comfort index Pct.

Speed km/h	Percentage dissatisfied passengers Pct around stop Oosterheem			
	Curve transition pos. 3100 (km 2.2)		Curve transition pos. 3300 (km 2.5)	
	% sitting	% standing	% sitting	% standing
60	7	25	5	19
70	13	42	7	23
80	20	61	15	42

CONCLUSION

The use of dynamic simulation tools such as VAMPIRE[®] provides the track engineer with the ability to target maintenance where it is most needed, by considering the complete interaction between vehicles and the track. It also allows identification of additional sites where, despite the track being within standard, there is a significant risk of derailment due to an interaction with the vehicle response. Such an approach has the potential to drive a step change in the way track maintenance standards are determined, resulting in:

- Optimised track maintenance to minimise derailment risk,
- Increased profit with a reduction in unnecessary maintenance,
- An improvement in overall ride quality.

The project described in this paper has shown that this approach can be applied successfully in practice, allowing optimised safety limits to be defined, from which intervention and alert limits can be derived. HTM are now using this approach, with safety limits based on simulation of vehicle/track interaction being followed.

References

- [1] ProRail (2007). OHD00022-2. *Instandhoudingsspecificaties spoorgeometrie.*
- [2] Onderzoeksraad Voor Veiligheid (2008). *Ontsporingen bij RandstadRail.*
- [3] Grimes, C.A, Hunt G.A. & Wilson, S. (2007). *A new tool for planning vehicle dynamics based maintenance.* Railway Engineering 2007.