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TOMAS KARIS Track Irregularities for High-Speed Trains

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Evaluation of their correlation with vehicle response

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Master of Science Thesis
Stockholm, Sweden 2009

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Preface and acknowledgements

This is the outcome of my work at the Department of Aeronautical and Vehicle Engineering at the Royal Institute of Technology (KTH) in Stockholm 2009 constituting my Master of Science thesis. It is a part of the Swedish research and development programme Gröna Tåget (the Green Train) and has been carried out in cooperation with Banverket (the Swedish Rail Administration) and Bombardier Transportation, Västerås.

The financial support from Banverket is gratefully acknowledged as well as support from KTH, Banverket and Bombardier Transportation staff:

Thanks to my supervisor Professor Evert Andersson, KTH, for his great knowledge and experience within the topic. His comments and guidance have been of excellent help.

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The above mentioned persons have been part of a reference group during my work. Thanks once again for valuable input and discussions at our meetings during my work.

Also thanks to Lars Andersson, Interfleet Technology, for helping me when I needed to retrieve more data from the on-track tests.

To my girlfriend, who can stand my talk about trains every now and then.

Stockholm, December 2009

Tomas Karis

Abstract

An important topic within railway engineering is track irregularities, i.e. the geometrical deviations from an ideal track alignment. This is of special interest to high-speed operations. Depending on how the track is aligned, different responses will be recorded in a passing vehicle, such as dynamic impact forces as well as motions, jerks and vibration. Track irregularities are surveyed and corrected on a regular basis according to appropriate standards.

This report covers firstly a literature survey done to investigate the current standards, both national and international. Secondly the current report presents an evaluation of track irregularities and on-track tests, carried out 2008 within the ”Gröna Tåget” (Green Train) research programme in Sweden, where vehicle responses are correlated to track irregularities. Both parts are important for recommendations on an updated track geometry quality standard that covers higher speeds than today’s maximum of 200 km/h in Sweden.

The literature survey shows that the track irregularity limit values specified in the BVF 587.02 standard used by Banverket (the Swedish Rail Administration) today are among the strictest of the ones investigated, except for vertical irregularities, while the European standard EN13848-5 is generally one of the most liberal. This comparison is however not entirely correct since the definitions of track irregularity quality levels differ between the standards.

An evaluation of on-track tests done in Sweden for ”Gröna Tåget” at 250 – 300 km/h has been conducted. In the evaluation maximum wheel-rail forces were compared to the peak irregularity on the same track section, in order to see a possible correlation. Ride comfort indices depending on jerks and vibration were compared to the standard deviation of track irregularities.

From the track irregularities and the on-track tests it is concluded that the high lateral quality of the test tracks makes it is hard to find any clear correlation between lateral forces and lateral isolated defects, as well as between lateral ride comfort and lateral standard deviation. The correlation in the *vertical* direction is higher however: there is generally a strong correlation between vertical wheel-rail forces and vertical isolated defects, especially in the 3 – 10 m wavelength range. The correlation is generally weaker between vertical ride comfort and vertical standard deviation of the track irregularities, but is still strong enough to suggest there is a relation. The lateral track shift forces’ root mean square over 100 metres was evaluated against the mean track gauge over 100 metres. It shows a significant increase in force when the mean track gauge was less than 1434 mm.

From the studies and evaluations made so far, the preliminary conclusion is that the lateral limit values in BVF 587.02 are strict enough also for higher speeds than 200 km/h. The vertical limit values however should be stricter at higher speeds, as well as the adherence to the limits. Further, the combination of lateral and cant irregularities (called “samverkan” in Swedish) shows similar response as lateral irregularities. This could be an effect from the high lateral quality of the track, as well as high cant quality. The track gauge change over 10 metres seems possible to discard in favour of the track gauge mean value over 100 metres. For speeds over 270 km/h the mean track gauge over 100 metres should not be less than 1434 mm, which is in agreement with international standards.

Further investigation, preferably made by vehicle-track dynamic computer simulations, is needed in order to find more general conclusions since the presented results only apply to one train type (the ”Gröna Tåget” test train). In some cases also a larger variation of the track irregularities is needed to achieve general and reliable conclusions.

Notations and abbreviations

Notation	Explanation	Unit
a	Acceleration	m/s^2
a_y	Track plane acceleration	m/s^2
AL	Alert limit	mm or mm/m
$B(f)$	Frequency weighting function	-
C_c	Continuous comfort, an ISO quantification of ride comfort	m/s^2
$D1$	Wavelength range: 3 – 25 m	m
$D2$	Wavelength range: 25 – 70 m	m
$D3$	Wavelength range: 70 – 150 m (vertical) 70 – 200 m (lateral)	m
f	Frequency	Hz
G	Track gauge	mm
h	Cross level	mm
IAL	Immediate action limit	mm or mm/m
IL	Intervention limit	mm or mm/m
L	Wavelength	m
l	Sleeper distance	m
Q	Vertical wheel-rail force	N
R	Horizontal curve radius	m
R_{xy}	Correlation	-
S	Lateral track shift force, see also $\sum Y$	N
s	Samverkan (combination)	mm
v	Vehicle speed	km/h or m/s
Y	Lateral wheel-rail force	N
Y/Q	Flange climbing ratio	-
y_p	Lateral deviation of track	mm
$\ddot{y}^*$	Lateral acceleration in carbody	m/s^2
z_p	Vertical deviation of track	mm
$\ddot{z}^*$	Vertical acceleration in carbody	m/s^2
Δr_l	Change in rolling radius for left wheel	mm
Δr_r	Change in rolling radius for right wheel	mm
Δy	Change in lateral position of a wheelset	mm
λ_{eq}	Equivalent conicity	-
$\sum Y$	Sum of lateral wheel-rail forces on a wheelset, see also S	N

Abbreviation	Explanation
ALS	Active Lateral Suspension
ATC	Automatic Train Control
BV	Banverket (The Swedish Rail Administration)
BVF	Banverkets Författningssamling (Banverket Standards)
CEN	Comité Européen de Normalisation (European Committee for Standardization)
D track	Down-track (southbound track)
EN (e.g. EN13848)	European Norm
HS TSI	High-Speed TSI (see TSI below)
ISO	International Organisation for Standardization
JR East	East Japan Railway Company (JR 東日本)
KTH	Kungliga Tekniska Högskolan (The Royal Institute of Technology)
MIT	Massachusetts Institute of Technology
PSD	Power Spectral Density
QN1, QN2, QN3	UIC 518 track quality levels, best to worse
RMS	Root Mean Square
TSI	Technical Specification for Interoperability
TQI	Track Quality Index
U track	Up-track (northbound track)
UIC	Union Internationale des Chemins de Fer (International Union of Railways)
Wz	Wertungszahl, a measure of discomfort

Contents

1 Introduction

For trains running up to 300 km/h or more, safety, maintenance needs and comfort are three big issues. These are related to both the vehicle itself, but also the track it is running on. In order to build and maintain a functioning infrastructure for these high-speed trains, certain norms and standards are needed to make sure that all infrastructure managers provide a safe and comfortable track.

Another issue is to be able to run at speeds above 200 km/h on existing conventional tracks. Sometimes high-speed trains must run to and from the high-speed line on conventional tracks, in particular near the endpoints of each run. There is also a need to run at increased speeds on conventional track on relations where no high-speed line is built. Travel times to cities and villages located outside the dedicated high-speed line will thus become shorter.

There is a research and development programme in Sweden called ”Gröna Tåget” (the Green Train) that aims to develop technology that can be used in a new, modern high-speed train for speeds at 250 km/h and above, being suitable also for Nordic conditions, in particular the harsh winter climate. The train is supposed to supersede the current X2000 tilting trains that were introduced in the early 1990’s and will also be able to run on future high-speed lines, which are currently in the planning stage. Due to the fact that there is today no existing dedicated high-speed railway line in Sweden, one of the issues is to be able to run trains comfortably and safely on parts of the existing rail networks even at speeds above 200 km/h.

The ”Gröna Tåget” programme has performed several on-track test runs 2006 – 2009 with a modified Bombardier Regina train and has also set a new speed record on a conventional railway in Sweden with 303 km/h in September 2008. This indicates that it is possible to run faster on a conventional track than the praxis of today (200 km/h) and it is therefore interesting to see how the train and tracks are responding to each other at these speeds. Many parameters can be modified on a train to improve its running characteristics, but not all interoperable European high-speed trains can be anticipated to be improved in this way. To make sure that a railway’s condition is good enough for carrying different kinds of train services, there are many standardisation documents, both national and international. These contain information about track geometry (built geometry and irregularities), track forces, wear parameters and other characteristics that are associated with running performance from the track’s point of view. They can be used, for example, to investigate if a track is in need of maintenance to sustain comfortable and safe train services.

This report will investigate the current standards and documents about track irregularities and compare them with each other. Extensive comfort and track force evaluation of the ”Gröna Tåget” tests from summer 2008 is also done to find out what level of track irregularities can be accepted for different speeds.

The goal of the present work is to be part of the basis for recommendations on a new Swedish standard for geometrical irregularities of the track with admissible speeds above 200 km/h. General European standards (EN) should be seen as minimum requirements.

2 Literature study

This chapter describes standards and other documents that cover track geometry quality. It starts with national and international standards and continues with other reports and research papers on the subject. All the documents define track geometry quality and the corresponding limit values. Section 2.3 contains a summary and comparison between the different standards.

In several standards the irregularities in *y*- and *z*-directions (refer to Figure 2-1 for definition) are called *alignment* and *longitudinal level* respectively. This can be a bit confusing: in the *z*-direction, for example, the *vertical* track irregularities are defined as irregularities in the *longitudinal level*. In this report track irregularities in the *y*-direction is simply called *lateral irregularities* and irregularities in the *z*-direction *vertical irregularities*.

2.1 National and international standards

2.1.1 EN13848-1

The European standard EN13848-1[1] specifies the characteristics of the track geometry and defines those parameters that are used in the series of EN13848 (Part 1 to Part 6). The different characteristics include track gauge, longitudinal level (here called 'vertical'), cross level, alignment (here called 'lateral') and twist and they are described below. Parts 2 to 4 cover measuring systems: track recording vehicles (Part 2), track construction and maintenance machines (Part 3) as well as manual and lightweight devices (Part 4). These parts will not be discussed, as they are out of scope of this report.

The definitions of the running surface and coordinate system, used when measuring track geometry from EN13848-1 (Figure 2-1), are also used in this report.

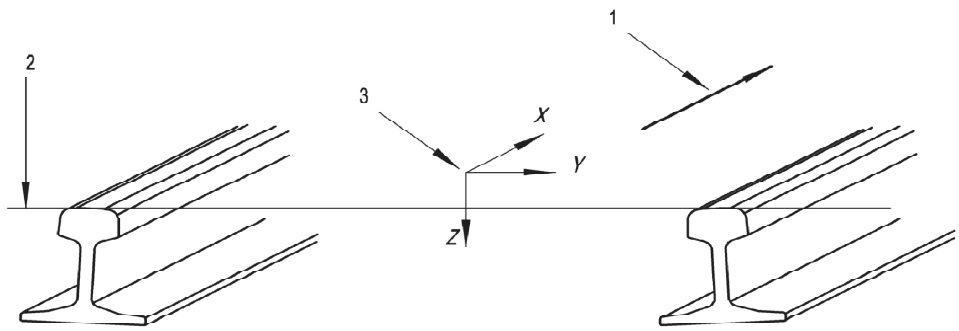


Figure 2-1 ***Track geometry definitions.*** *1: running direction, 2: running surface and 3: coordinate system* ***[1]****.*

For each characteristic a number of properties are defined. These are the definitions, the measurement method and wavelength ranges where applicable. The resolution of the measurements is at least 0.5 mm for all track geometry characteristics but the uncertainty and the range of the measurements are defined appropriate to each characteristic. The analysis method is also different depending on what kind of irregularity being evaluated.

In Annex B in [1] a number of other parameters that can be measured to help understanding the track geometry and vehicle interaction, but those are left out as they do not add to the understanding of this report.

Track gauge

EN13848-1 states: "Track gauge, *G*, is the smallest distance between lines perpendicular to the running surface intersecting each railhead profile at point *P* in a range from 0 to z_p below the running surface. z_p is always 14 mm." See Figure 2-2.

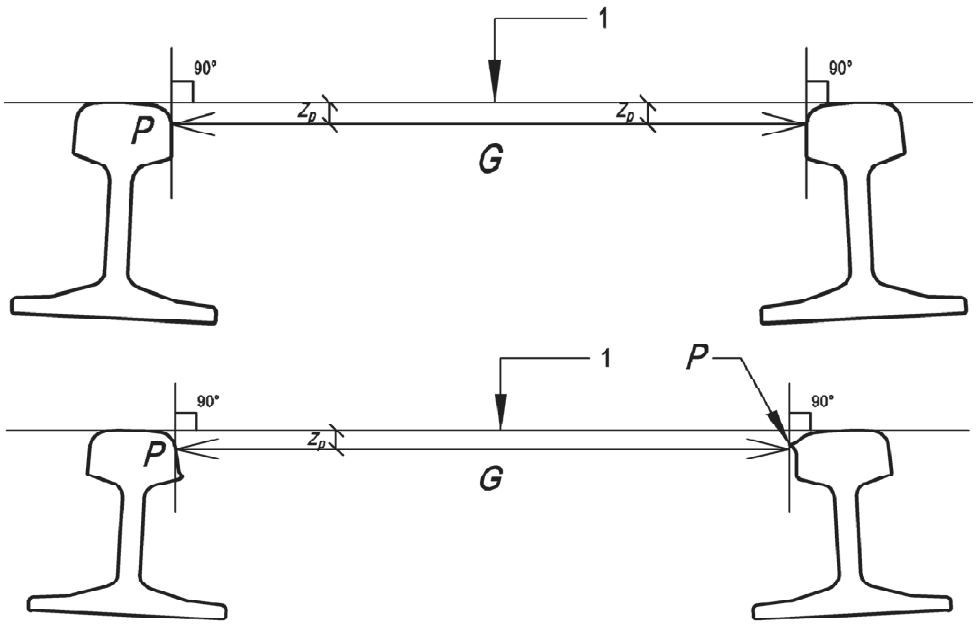


Figure 2-2 ***Track gauge definition.*** *Track gauge G for new rails (top) and worn rails (bottom), where 1 is the running surface* ***[1]****.*

The standard nominal track gauge in Sweden and most other countries in Europe is 1435 mm (see CR INF TSI [2]). Nominal track gauges smaller than 1435 mm are called narrow gauge (e.g. 1067 mm in Japan, South Africa and Queensland) and those wider than 1435 mm are called broad gauge (e.g. 1524 mm in Finland and former Soviet Union as well as 1668 mm in Spain and Portugal). Modern high-speed railways worldwide are built with the standard track gauge.

Vertical (Longitudinal level)

EN13848-1 states: "Deviation $z_{p'}$ in z-direction of consecutive running table levels on any rail, expressed as an excursion from the mean vertical position (reference line), covering the wavelength ranges stipulated below and is calculated from successive measurements ... " [1]. See Figure 2-3 below.

The wavelength ranges referenced to are defined as *D1* = 3 – 25 m, *D2* = 25 – 70 m and *D3* = 70 – 150 m. A note on page 13 in [1] suggests that *D1* = 1 – 25 m should be used in order to detect short wavelength irregularities. These wavelength ranges are used in all European Norms (EN).

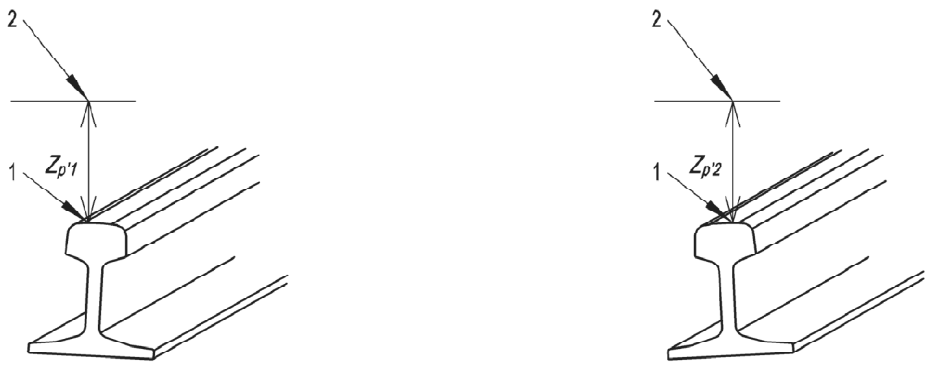


Figure 2-3 ***Vertical deviation definition.*** *Vertical deviations $z_{p'}$ for each rail with 1: running table and 2: reference line* ***[1]****.*

Cross level (Cant)

EN13848-1 states: "The difference in height of the adjacent running tables computed from the angle between the running surface and a horizontal reference plane. It is expressed as the height of the vertical leg of the right-angled triangle having a hypotenuse that relates to the nominal track gauge plus the width of the rail head rounded to the nearest 10 mm ... " See Figure 2-4 below.

The cross level, or cant, is usually denoted h with different indices [3][4]: h_t for the (nominal) cant in a circular curve, h_{eq} for the equilibrium cant, h_d for cant deficiency and h_e for cant excess. Cant is applied in horizontal curves to decrease the lateral forces and make the curve more comfortable to pass through. This is achieved mainly because a larger part of the accelerations or forces are directed perpendicular to the track plane rather than parallel.

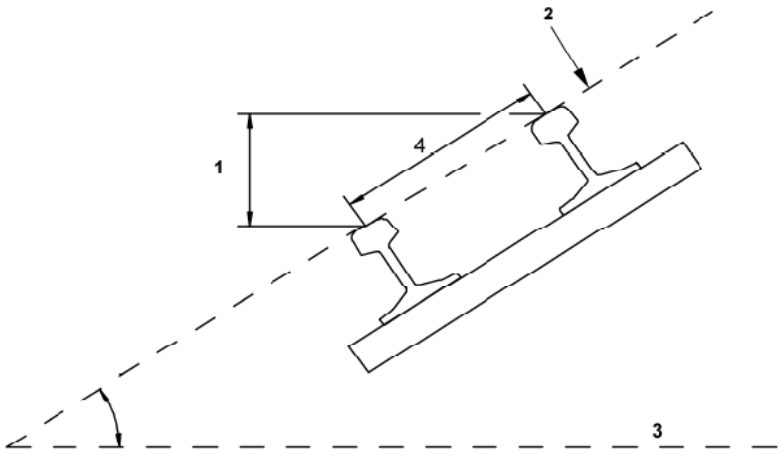


Figure 2-4 ***Cross level definition.*** *1: cross level, 2: running surface, 3: horizontal reference plane and 4: hypotenuse* ***[1]****.*

Lateral (Alignment)

EN13848-1 states: "Deviation y_p in y-direction of consecutive positions of point P ... on any rail, expressed as an excursion from the mean horizontal position (reference line) covering the wavelength ranges stipulated below and calculated from successive measurements ... ". See Figure 2-5 below. Point P can be found in both Figure 2-2 and Figure 2-5 in this report.

For lateral deviations, the following wavelengths shall be considered: *D1* = 3 – 25 m, *D2* = 25 – 70 m and *D3* = 70 – 200 m. A note on page 16 in [1] suggests that *D1* = 1 – 25 m should be used, in order to detect short wavelength irregularities.

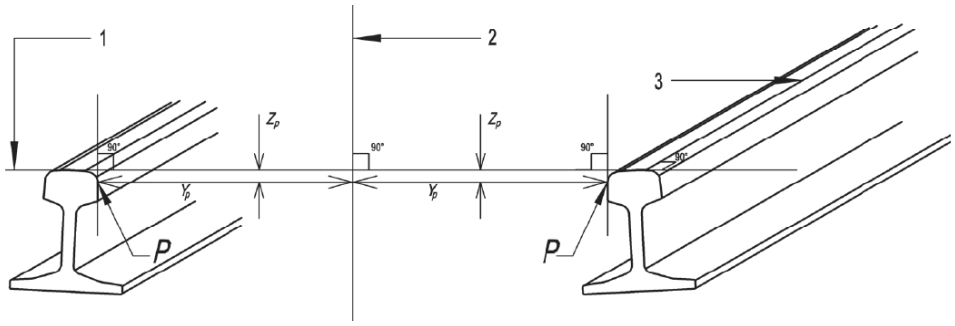


Figure 2-5 ***Lateral deviation definition.*** *Lateral deviations y_p for each rail with 1: running surface, 2: reference line and 3: centre line of running table* ***[1]****.*

Twist

EN13848-1 states: "The algebraic difference between two cross levels taken at a defined distance apart, usually expressed as a gradient between the two points of measurement."

The twist can be expressed as a zero to peak or mean to peak value for isolated defects. It is measured with a base of 3 or 6 metres and can be expressed in ‰ or mm/m.

2.1.2 EN13848-5

EN13848-5[5] specifies the quality levels for the track geometry defined in EN13848-1. There are three levels when a track's geometry differs from the theoretical alignment: Alert Limit (AL), Intervention Limit (IL) and Immediate Action Limit (IAL). Refer to Table 2-1 for a further description of the levels.

Table 2-1 EN13848-5 track quality levels.

AL	If a limit value is exceeded at this level, an action that corrects the error has to be done during the next scheduled maintenance
IL	If a limit value is exceeded at this level, an action that corrects the error has to be done before the next inspection
IAL	If a limit value is exceeded at this level, an action that lowers the risk of derailment has to be done immediately (maintenance, speed restrictions etc.)

EN13848-5 mainly covers IAL values for track gauge, vertical and lateral irregularities as well as track twist, since it is the only normative quality level. Cross level is considered tied to twist and cant deficiency, which can vary significantly between different networks and thus no limits are specified. It is also stated that the AL and IL levels depend more on the maintenance policy and therefore they are considered informative. While the normative IAL values are found throughout the main text in [5], the informative AL and IL values can be found in Annex B of EN13848-5.

2.1.3 prEN13848-6

This is the draft to a new document in the EN13848 standard: Part 6. prEN13848-6 [6] will describe and classify track geometry quality and will also take into consideration how the classification can be used. The quality is usually measured as a number calculated from the track irregularities and is called Track Quality Index, TQI.

The method of calculating TQI differs from country to country and both isolated defects and standard deviations can be used. Most methods rate the defects or standard deviations in comparison to the limit values (i.e. AL, IL and IAL for EN13848-5 limit values) in order to quantify how good or poor the track is. This can of course be applied to individual sections or even the whole network [6].

2.1.4 EN14363

EN14363[7] defines acceptable running characteristics of rail vehicles, i.e. limit values for certain characteristics that can be measured, to ensure safety as well as tolerable levels of acceleration and track deterioration. Vertical and lateral track forces, as well as running stability and accelerations of the tested vehicles shall be measured. Most of the running characteristics shall be determined by on-track testing, but EN14363 also specifies some static tests. The latter part is aimed to ensure safety against derailment on twisted tracks and to determine the sway characteristics of the vehicle, the rotational resistance of the bogies and the static vertical wheel forces. The sway characteristics test will show if the vehicle stays within the kinematic envelope or not and the rotational resistance test will determine the torque (and the lateral wheel-rail force) required to turn the bogie relative to the carbody in the track plane.

About testing methods

The standard also covers testing procedures to ensure that tests are done in a proper way. This also includes limit values for safety, track maintenance and ride comfort, for example vertical and lateral wheel forces and accelerations in bogies and the carbody for the different test sections: straight track or curves with different radii.

There are also specifications for the test tracks. They should correspond to the test sections mentioned earlier (straight track, different types of curves) and also have the different rail inclinations and profiles that the vehicle is supposed to run on. The rails should generally be dry, but other states can be tested where appropriate (for example slippery conditions due to rain and tree leaves). The test track should have different sections where the train should pass with a constant speed or constant cant deficiency in curves.

Track geometry specification and quality levels

In Annex C of EN14363 the track geometry of the test tracks to be used in the above mentioned tests is specified. The geometry types are straight or tangent track (R > 10 000 m), large radius curves, medium radius curves and small radius curves. Three quality levels are defined (Table 2-2) which almost follow the three levels in EN13848-5. The difference is that the QN3 level, which shall not be an IAL error but still worse than IL, is defined as a 30 % increase of the limits in QN2. Note that these quality levels only apply to vehicle acceptance tests [7].

Table 2-2 EN14363 track quality levels.

QN1	An error that should be repaired during next maintenance
QN2	An error that should be repaired within a short time frame (before next maintenance)
QN3	The track is of poor quality, but still of a tolerable level. QN3 errors are 30 % worse than QN2 errors.

2.1.5 Technical Specification for Interoperability: High-speed railways

The Technical Specification for Interoperability (TSI) for High-speed tracks [8] applies to all high-speed railways in Europe, in order to make cross-border rail services in Europe easier and more efficient. The document covers everything from the nominal track gauge and distance between centre lines to platform heights and maximum pressure in tunnels. The parts being within the scope of this report are of course the parts concerning track geometry and the corresponding quality levels.

The quality levels of the high-speed TSI are specified for the range of 160 – 300 km/h, but the only quality levels defined are limits for equivalent conicity and limit values for the track gauge mean value to peak over 100 m. It is instead stated that the infrastructure manager should determine the lateral and vertical standard deviation limits for the Alert Limit, as well as the lateral and vertical limits for isolated defects (mean to peak value) for all quality levels. Further, the infrastructure manager should determine the limit values for isolated defects of track twist (zero to peak value) and gauge (nominal gauge to peak value). The mean track gauge over 100 m (nominal to mean value) should be determined for all three quality levels as well [8].

2.1.6 UIC Code 518

The International Union of Railway's (UIC) document on track geometry quality at acceptance testing is UIC Code 518[9]. In similarity to EN14363, the main areas of the standard are vehicle acceptance tests and not track geometry, but a difference is that UIC 518 only covers running tests, whereas EN14363 covers both running and static tests.

One part describes the tracks that the vehicle to be approved, should run on. The quality levels used are the same as in EN14363 (Table 2-2) and the limit values for the different track geometry characteristics are also the same. Also here, remember that these quality levels only apply in vehicle acceptance tests. In the diagrams in Section 2.3 of the present report, the levels for EN14363 in the diagrams also apply to UIC 518 [9].

2.1.7 BVF 587.02

This document is the Swedish standard for track geometry quality (corresponding to EN13848-5 as well as prEN13848-6). The series of EN13848 Part1 – Part 6 have not been implemented in Sweden yet.

Except for limit values for the different track geometry characteristics, it describes what track geometry parameters that Banverket's track recording car STRIX is able to measure. The standard is somewhat stricter than EN13848-5, with some exceptions (see Section 2.3). BVF 587.02 [10] also uses a different quality level system than the European norm (Table 2-1 and Table 2-3). Two tables from BVF 587.02 have been appended in Appendix A to serve as a reference for the three levels A, B and C. Note that it lacks the mean track gauge over 100 metres, which will be discussed later in this report.

Table 2-3 BVF 587.02 track quality levels.

A	Accepted error level in new and newly corrected tracks. A few extreme values outside the limits are accepted
B	Maintenance level: errors should be corrected before this level is reached. A few extreme values outside the limits are accepted if monitored until adjustment
C	Errors on this level have to be corrected as soon as possible. Until it is fixed, actions have to be taken to ensure safety
Derailment risk	If this level is reached, traffic has to be stopped or, if possible, continue with speed restrictions and surveillance

It should be noted that only level C (and the "derailment risk" level) is forcing action and levels A and B are recommended levels for new tracks and maintenance respectively. Normally track irregularities should not be worse than level B quality before maintenance though [10].

2.1.8 Banenorm BN1-38-3

The Danish BN1-38-3[11] corresponds to EN13848-5. The track quality levels are a bit different compared to the other standards and most similar to the Swedish ones. For example there are two levels for new or newly maintained tracks, where others have one or none; also note that there is no level 2. Generally the Danish standard is stricter than the others.

Table 2-4 BN1-38-3 track quality levels.

0	The largest acceptable error level after final adjustment and 1 year adjustment for new tracks or track restoration
1	The largest acceptable error level after scheduled maintenance, "emergency" adjustment and follow-up maintenance for new and restored tracks
3	Errors on this level should be adjusted during next scheduled maintenance
4	Errors on this level have to be inspected within four weeks (two weeks where v > 160 km/h) after measurement. The errors shall be maintained within six months (three months where v > 160 km/h) to make sure they will not exceed the max/min level before next scheduled maintenance
Max/min	If an error on this level is found, actions have to be taken to lower the risk of derailment: close the line, reduce the speed or immediately maintain the track

2.2 Other documents on track quality

2.2.1 MiW Konsult AB's research about different standards

MiW Konsult AB's report[12] is a report for Banverket's high-speed railway project in Sweden and contains a draft of new track standards for high-speed railways and new quality classes (Q1-Q6). It also covers updated track standards for the current quality classes (K0-K5), discussing whether the current parameters that are measured constitute a good way of defining track quality. There is also a brief part about track deterioration for different train types.

The report compares different track standards and parameters to find a good base for the draft that is proposed. The draft's limit values are often stricter than those of other standards, but there are some exceptions. This is because the research the draft is based on shows that some of the very strict limits in the other standards do not need to be that strict from a safety and maintenance point of view. Note that no investigation of on-track tests and vehicle reaction to irregularities has been done, so the results are very dependent on other countries' limit values of different track quality levels.

The new quality levels that are proposed in MiW Konsult's draft follow the ones defined in BVF 587.02 (see also Table 2-3), but with some recommendations: level B errors have to be investigated (it is currently not required) and the introduction of mean track gauge over 100 metres, to mention a few.

Table 2-5 MiW Konsult's draft quality levels. *Source:* ***[12]****.*

A	Maximum error in new or newly maintained tracks
B	Errors that have to be maintained during next scheduled maintenance
C	Errors that have to be maintained before next scheduled maintenance, depending on the severity
D	The immediate action level: maintenance, lower speed or closing the line in order to reduce derailment risks

2.2.2 MIT paper: Estimation of rail irregularities

This document [13] proposes a method for estimating the track irregularities based on accelerations of regular passenger cars, instead of using special inspection cars. The accuracy of this method is reported to be acceptable on ideal conditions, but due to too much variation of load and speed of in-service trains, great variations were also recorded. The paper shortly mentions the standard irregularity levels of JR East's Shinkansen tracks and it seems most likely that the levels correspond to C level in Table 2-3.

2.3 Summary of track irregularities and their limits

Table 2-6 below compares the different track quality levels found in different standards. It is similar to the one found on page 14 in [12]. JR East is referring to East Japan Railway Company and the track quality limits described in Section 2.2.2. The quality level QN3 for test tracks in EN14363 differs slightly from the other immediate action limits since it is calculated as a 30 % increase of the QN2 limits. It does not require immediate action and is only used for vehicle acceptance tests. In BVF 587.02 there is no name for the immediate action level other than "errors with high risk for derailment" and in MiW Konsult's draft it is called D, so similarly the levels A, B, C and D will be used in this report. Note that AL and IL are only recommended levels in EN while IAL is normative.

Table 2-6 Comparison between different track quality levels.

Error level	EN 13848-5	EN14363, UIC 518	JR East (JP)	BN1-38-3 (DK)	BVF587.02 (SE)	MiW draft
Quality of new track				0/1	A	A
Action during next maintenance	AL	QN1		3	B	B
Action before next maintenance	IL	QN2/QN3	X	4	C	C
Immediate action	IAL	QN3		Max/min	"D"	D

Most track quality limits apply to the wavelength range *D1* (3 – 25 m), with optional or extra limits for *D2* (25 – 70 m) and sometimes *D3* (70 – 150/200 m). This is because generally the safety issues associated with track irregularities are connected to the shorter *D1* wavelengths and irregularities in the longer *D2* and *D3* are more a comfort concern. Are the wavelength ranges *D1*, *D2* and *D3* sufficient then? 1 – 25 metre wavelengths contain a wide frequency spectrum, from a few Hz up to almost 100 Hz with speeds around 300 km/h. Thus, it might be interesting to divide the 1 – 25 m range into smaller ranges, cf. Section 4.1.3.

The following sections contain diagrams for a visual comparison between different standards. These are for the AL values, refer to Appendix B for diagrams with both IAL and AL values (the IL value is used in one case where no IAL limit is defined).

2.3.1 Track gauge irregularities

The error limits for mean track gauge over 100 m are shown in Figure 2-6 below. The Swedish standard BVF 587.02 does not define any limits for mean track gauge over 100 metres. Instead there are limits for change of track gauge over 10 metres of track. However, it does not say anything about the track gauge itself, which instead is said to be controlled by isolated defects. For higher speeds, the mean track gauge over 100 metres is a more reasonable way to control the equivalent conicity and indirectly the stability; see Equation (1) below, ref [3]. Note that this definition differs from the definition in [14].

$$\lambda_{eq} = \frac{\Delta r_r - \Delta r_l}{2\Delta y} \tag{1}$$

In Equation (1) λ_{eq} is the equivalent conicity, $\Delta r_r - \Delta r_l$ the difference in rolling radius for right and left wheel for the lateral displacement Δy of the wheelset at the track level. Note that $\lambda_{eq}(\Delta y)$ itself is a non-linear function and that the track gauge has to be considered to calculate a single value of the equivalent conicity.

With a high equivalent conicity the wheelset risks an unstable behaviour, as a small lateral displacement will steer the wheelset excessively to compensate the displacement as opposed to the low equivalent conicity where a small lateral displacement will result in a more moderate steering of the wheelset. This of course only applies to wheelsets with a joint axle; a wheelset with free-rotating wheels has no steering ability in this respect.

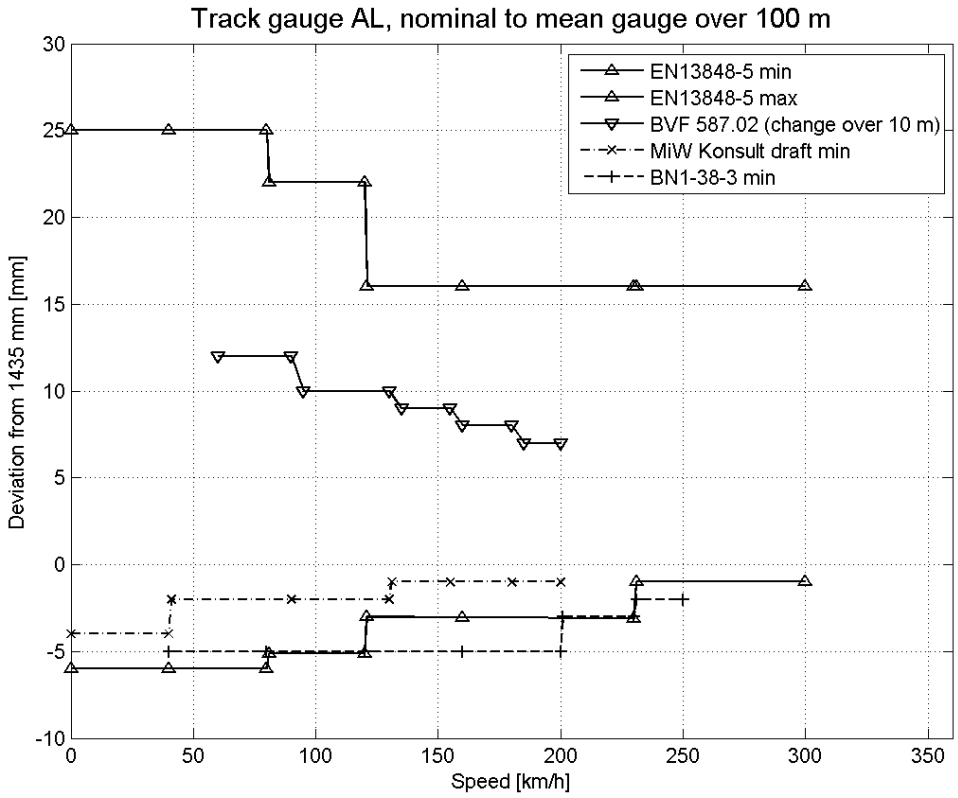


Figure 2-6 ***Example of mean track gauge limit values for different speeds.*** *Nominal track gauge to mean gauge over 100 m, deviation from 1435 mm, AL (see* ***Table 2-6****). Note that BVF 587.02 has no limit specified for 100 m.*

Figure 2-6 shows the AL limit values for nominal to mean track gauge over 100 metres. Note that the Danish BN1-38-3 and MiW Konsult's draft do not have a limit for maximum track gauge. The limit values in Figure 2-6 are connected to controlling the equivalent conicity for a number of standardised wheel and rail profiles, for example the UIC/ORE S1002 wheel profile and the UIC60 rail profile [3].

2.3.2 Vertical irregularities

With large and varying vertical irregularities, there is a risk of producing cracks in wheels and rails because of the large dynamic forces. Vertical irregularities are also a source of discomfort, because of accelerations of short wavelengths or vertical displacements of longer wavelengths.

The error limits for isolated defects, nominal to peak value, for different standards' AL are shown in Figure 2-7 below. The Danish standard closely follows the limits in the vehicle acceptance standard EN14363, but EN13848-5 is more admitting.

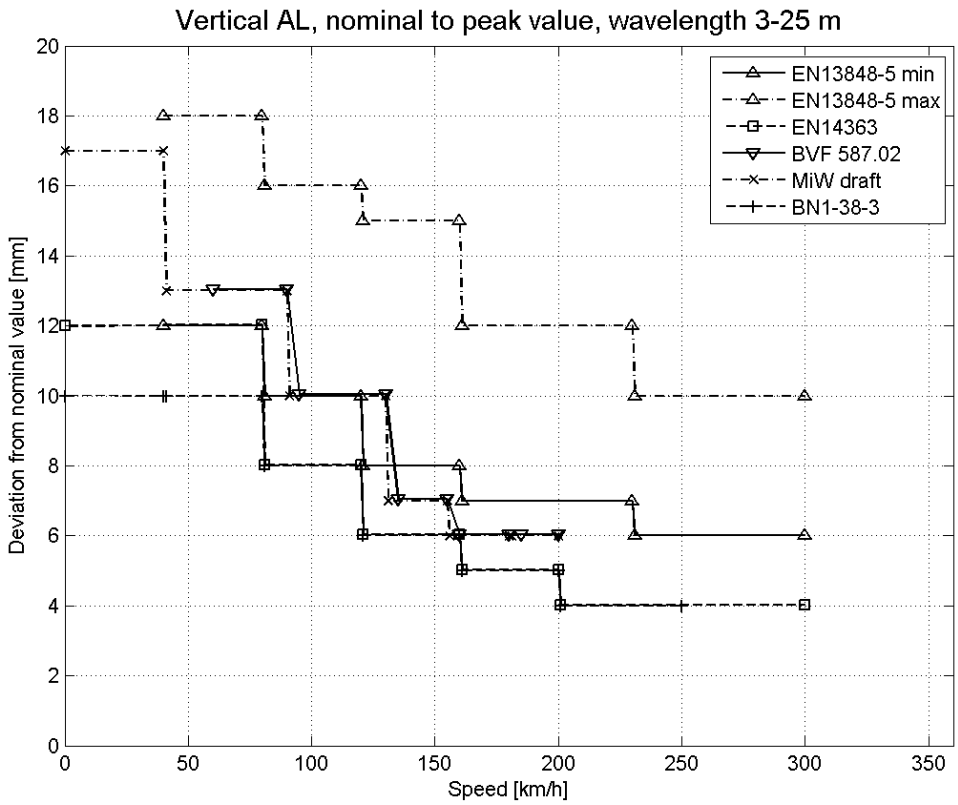


Figure 2-7 ***Example of vertical track irregularity limits for different speeds.*** *Nominal to peak value, AL (see* ***Table 2-6****).*

For the AL and IL limits EN13848-5 specifies a range instead of a single value for every speed interval in order to make it easier for different railway administrations to adopt their maintenance policies. This applies to the EN13848-5 lateral irregularities limits in Section 2.3.4 as well. In addition it should be mentioned that the target *standard deviation* with respect to comfort in BVF 587.02 is 1.1 mm for 1 – 25 m wavelengths and speeds of 145 – 200 km/h.

2.3.3 Cross level irregularities

For the cross level, no limits are specified in EN13848-5, because the safety risks with cross level irregularities are related to the limits for twist and cant deficiency and should be decided by each infrastructure manager. Neither this report will concentrate much on cross level errors, for the same reason [12]. However, these kinds of errors affect comfort and dynamic movements of the vehicle and should thus be taken into account when maintaining the track.

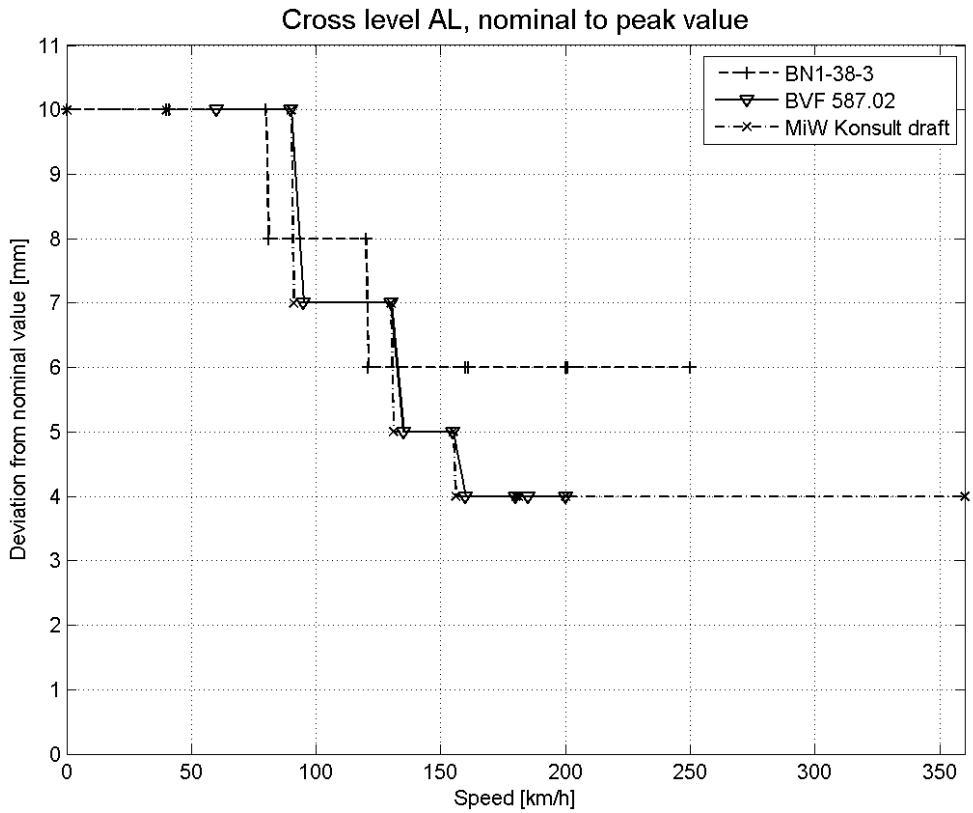


Figure 2-8 ***Example of cross level (cant) limits for different speeds.*** *Nominal to peak value, AL (see* ***Table 2-6****).*

2.3.4 Lateral irregularities

Especially in curves, where the outer wheels are more or less guided towards the outer rail, the lateral irregularities are important to control. Too large irregularities would produce high dynamic loads as well as uncomfortable behaviour.

The error limits for isolated defects for mean to peak value are shown below in Figure 2-9. The appearance is similar to Figure 2-7: BN1-38-3 and EN14363 follow each other almost identically while EN13848-5 accepts larger deviations.

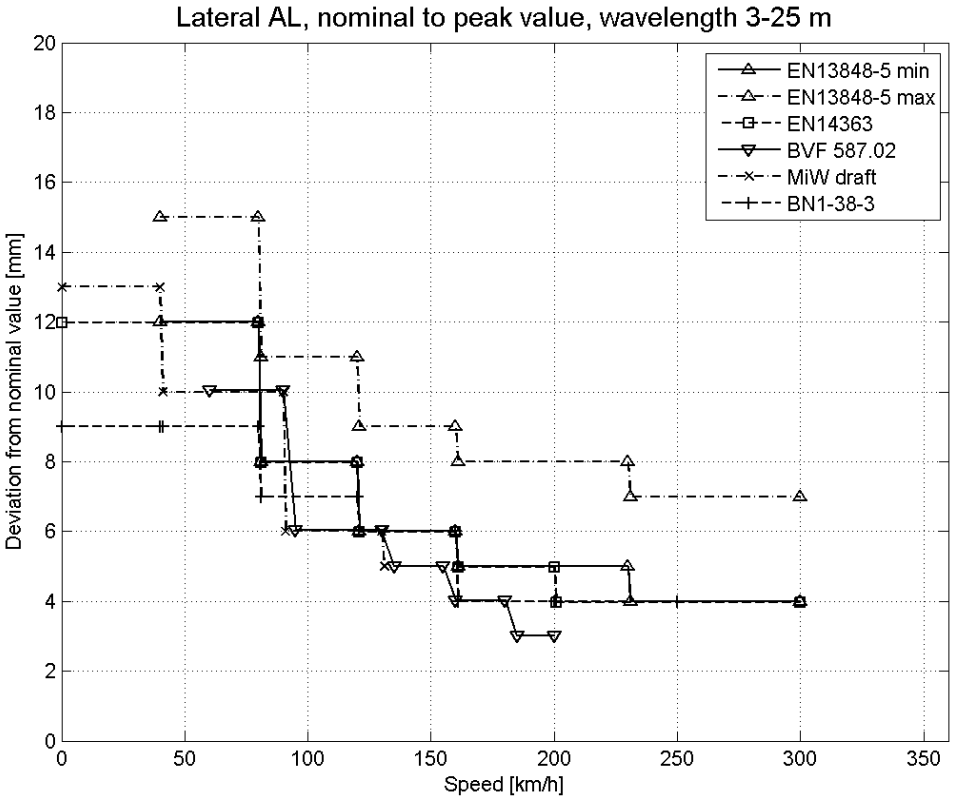


Figure 2-9 ***Example of lateral track irregularity limits for different speeds.*** *Nominal to peak value, AL (see* ***Table 2-6****).*

In addition it should be mentioned that the target *standard deviation* (with respect to comfort) in BVF 587.02 is 1.1 mm for speeds of 145 – 200 km/h, wavelength 3 – 25 m.

2.3.5 Twist

The limits for isolated defects for zero to peak value of twist are shown in Figure 2-10. Note that it is measured in mm/m, while in Sweden it is usually measured in mm per 3 or 6 metre base. Too much twist can lead to one or more wheels being lifted from the rail and might cause derailment.

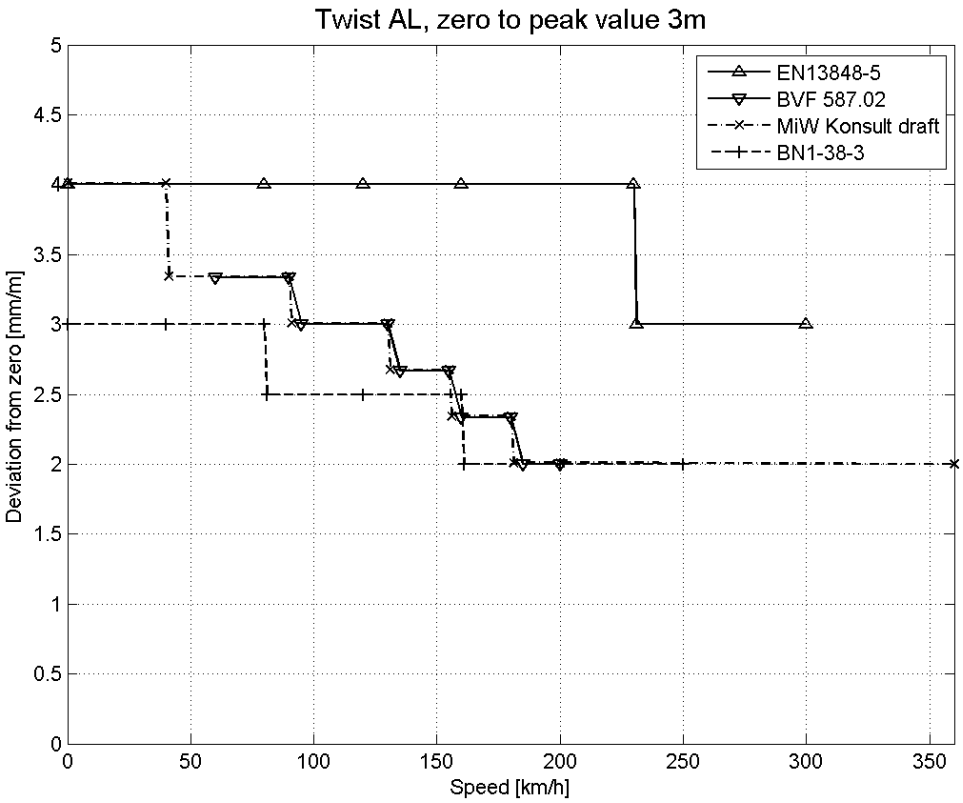


Figure 2-10 ***Example of track twist irregularity limits for different speeds.*** *Zero to peak value, AL (see* ***Table 2-6****).*

The twist of the track shows the error in track cant along the track and applies to straight track as well. A reason for an uneven running surface (Figure 2-1) can be softer ground or subgrade under one of the rails or that the ballast's strength has changed.

3 Track deterioration and maintenance

3.1 Effects on tracks and wheels

When a train runs on a track, no matter how smooth it might run, there is always some track deterioration. This can be seen especially in curves where the rail wear is particularly visible. There is also wear on the wheels, which will eventually make the wheel cone shape hollow and produce a higher conicity or a thinner flange. These defects are maintained by turning or changing the wheels.

3.1.1 Track-friendly vehicles

A track-friendly train causes minor deterioration of the track, which in turn lowers the cost and need for maintenance as well as cost for renewal of the track components more often.

Trains that are track-friendly usually have soft bogies, which typically is a bogie with soft longitudinal and lateral primary suspension to allow the wheelsets to yaw slightly relative to the bogie frame in curves and allow full or partial *radial steering in curves* with relatively small radius [3]. This reduces wear of wheels and rails as well as curving squeal. The price paid for allowing better curve negotiation is often said to be a lower critical speed, the speed at which the train ride becomes unstable, so-called hunting. However, this challenge can be mastered by using appropriate suspension and damping parameters. An example of a train with soft bogies is the test train in Section 4.1.1. It has run a number of tests at up to 300 km/h with improved, soft bogies.

According to [12], running on high-speed lines will cause less wear compared to running the same vehicle on conventional lines, which is mainly due to a larger amount of curves with large radii. This means that it might be less important with soft radial steering bogies on high-speed vehicles than for vehicles on conventional lines. For services to cities outside the high-speed network, it is still important to have a track-friendly vehicle however.

Independent of the curving performance there are also other vehicle characteristics of great importance for track-friendliness. Important parameters are the *static axle load* and the *unsprung mass*. These parameters are also most important for the track deterioration. Also the weight of centre of gravity has some importance.

3.2 Maintenance

Maintaining a railway network involves many different aspects. In order to properly remove the defects and irregularities of the track, it needs to be measured. This is typically done with a track recording car; in Sweden Banverket mainly uses STRIX (see Section 4.1.3).

Different track geometry parameters are measured, and then filtered in different wavelength ranges if applicable. The results are compared to the limit values of the track quality standard, to determine where maintenance is needed.

3.2.1 Alignment techniques

There are some basic techniques for aligning the track. The work is done with maintenance machines that can lift up the track and move (force) it into place again. This is done laterally and vertically, as well as for the cant (cross level). The track gauge cannot be changed easily after the rails are fastened to the sleepers. Only minor changes in track gauge can be done by grinding the inside of the rails to a wider gauge.

Depending on the wavelengths of the irregularities, different methods are used. Maintenance in a wavelength span with very short wavelengths requires grinding rather than using the conventional method of lifting and moving the track itself. In Sweden, Banverket use grinding to maintain defects in the 0.03 – 0.3 m and 0.3 – 1 m wavelength ranges [24].

3.3 Track alignment vs. maintenance costs

As mentioned earlier, some standards are stricter than others. These track quality levels are formed by experience, maintenance policies, results from research et cetera. One could believe that having a perfect track alignment, i.e. completely level, with constant 1435 mm track gauge et cetera, would be the most preferable. As will be seen later in this report, the "Gröna Tåget" test train run with fully acceptable vehicle responses on a track with both tighter and wider track gauge than the nominal 1435 mm. In fact, the Swedish speed record of 303 km/h was set on a track with tighter track gauge than 1435 mm. There were also several sections where either the vertical or lateral track quality was close to the allowed limits for a 200 km/h track.

But having a perfect track in every aspect might not be favourable since it is also costly. Every passage of a train makes some wear on the rails and contributes to track settlement vertically and laterally, i.e. disturbing the track geometry. This means that the maintenance costs can be very high with the wrong combination of vehicles and maintenance policies.

3.3.1 Track access charging

To run train traffic, a track access fee has to be paid to the infrastructure manager, which in Sweden is Banverket. The infrastructure manager is usually responsible for the maintenance of the tracks, which can be costly with a high traffic load. One way to be compensated for the costs for track deterioration is to use a track access charging model based on how track-friendly a train is. A vehicle that causes significant deterioration could pay more to have access to the track. In Sweden, Banverket is planning to introduce track deterioration-based fees for trains [15].

3.4 Track irregularities vs. other influences

The wheel-rail forces can be divided into different components:

- quasistatic forces, due to axle load and curving
- unstable (sinusoidal) running behaviour
- sleeper passing
- track irregularities

Q forces are affected by sleeper passing, the quasistatic curving forces, track irregularities and to some extent unstable (sinusoidal) running behaviour. *S forces* are affected mostly by unstable (sinusoidal) running behaviour, but also by quasistatic forces in curves and track irregularities.

The ride comfort is also affected by different components: accelerations from track irregularities, vehicle running behaviour and quasistatic accelerations in curves. Of these, the *vertical* ride comfort is mostly affected by the vertical track irregularities, but also by the running behaviour. In general the *lateral* ride comfort is mostly affected by track irregularities too, but also by the running behaviour of the train and quasistatic curve accelerations.

The results in Chapter 4 should be evaluated with this in mind, as most of the vehicle responses also need other explanations than only the track irregularities.

The track irregularities mentioned above can be divided into its different parameters. Table A.1 from Annex A in [5] (Table 3-1 below) shows an overview of the track geometry parameters and their predominant influences on vehicle responses.

Table 3-1 ***Vehicle responses to different track geometry parameters.*** *X is from EN13848-5, ⊗ is added in this report. Source: Table A.1 in* ***[5]****.*

Responses	Track gauge	Vertical	Twist/cross level	Lateral
$\sum Y$	X		X	X
Q		X	X	X
$\ddot{y}^*$	⊗		X	X
$\ddot{z}^*$		X		
Y/Q	(X)	X	X	X

In the above Table, $\sum Y$ is the wheelset sum of lateral wheel-rail forces (the so-called track-shift force; in this report, S will be used instead of $\sum Y$.), Q is the vertical track force from each wheel, $\ddot{y}^*$ is the lateral acceleration of the carbody, $\ddot{z}^*$ is the vertical acceleration of the carbody and Y/Q the flange climbing ratio. UIC 518 defines a limit value of 0.8, c.f. Equation (2), based on the sliding mean value over 2 m of the Y/Q ratio [9].

$$\frac{Y}{Q} \leq 0.8 \tag{2}$$

The vehicle responses being of interest in this report are the lateral and vertical forces S and Q as well as the accelerations $\ddot{y}^*$ and $\ddot{z}^*$. The latter two are used when calculating the ride comfort (e.g. discomfort) values. The flange climbing ratio will not be considered here, since the pure vertical and lateral responses and irregularities are of most interest [5]. Further on high-speed track the track twist should never be so high that Y/Q reaches high (and dangerous) values.

4 "Gröna Tåget" test results vs. track irregularities

4.1 General background

"Gröna Tåget" (the Green Train) is a research, development and demonstration programme in Sweden. It was started by Banverket in 2005 in cooperation with the major part of the Swedish rail sector, including KTH and Bombardier Transportation and is aimed to continue until 2011. "Gröna Tåget" should serve as a bank of ideas, proposals and technical solutions for a future generation of high-speed trains for Swedish and Nordic conditions. The train supplier Bombardier Transportation participates in the programme with its own test train called "Regina 250".

A number of on-track tests were done during the summer of 2008 with a modified Regina train. In September 2008 a new Swedish speed record was also set when the train achieved 303 km/h on a conventional track. During the test runs large amounts of data were collected and among these, the wheel-rail forces and ride comfort values. In connection with the test runs, track irregularities were measured by Banverket. The analysis in this report is based on comparisons and correlations between track irregularity data and measured response from the test train.

The track data from Banverket and "Gröna Tåget" were evaluated using a Matlab® [16] programme made by the author. The programme matches track data from Banverket and vehicle response data from "Gröna Tåget" tests 2008 and produces diagrams of Q and S forces against isolated defects of track irregularities and the root mean square of the track gauge. Another, similar programme matches ride comfort data to the standard deviation and mean values of track irregularities.

4.1.1 "Gröna Tåget" summer tests 2008

The test train that is used in "Gröna Tåget" on-track tests is a modified two-car Bombardier Regina (Figure 4-1), which is a wide-body regional train with a maximum permissible speed of 200 km/h in regular service. The test train has axle loads of about 15,5 tonnes on all axles.

To allow higher test speeds, all of the traction gears have been changed. One of the cars has bogies with active lateral suspension (ALS) and modified secondary suspension, both cars has radial steering "soft" bogies. One bogie features a permanent magnet motor (PM motor) and testing has also been done with bogie skirts. From March 2009 (except June – August) the test train has been in regular service with the PM motor and ALS active in order to do a long time in-service test [17].

The data from "Gröna Tåget" is recorded and evaluated by Interfleet Technology. One bogie has instrumented wheelsets which record vertical and lateral wheel-rail forces, in addition accelerations on the bogie frames are recorded to ensure that the vehicles are running stably. The comfort data is derived from accelerometers on the carbody floor above bogies and in the middle of the car. The vertical and lateral forces are sampled at 300 Hz and filtered with a 20 Hz low-pass filter according to UIC 518. The vertical forces are also sampled at 600 Hz and filtered with a 140 Hz low-pass filter to be able to evaluate effects that cannot be seen in the 20 Hz filtered forces, in particular the high-frequency forces resulting from the unsprung mass, track irregularities and sleeper-passing effects. The force evaluation is described further in Section 4.1.2.

The data is then evaluated over a number of sections, which are defined in UIC 518 and depend on the speed. They are all listed in the data files with their respective start and stop km-points, length, type of geometry, target speed, et cetera.

Figure 4-1 ***"Gröna Tåget" test train.*** *Source: Evert Andersson.*

The vehicle speed in the evaluated tests range from 150 to 300 km/h, depending on the type of test section. In UIC 518, tests at 10 % over-speed, or 10 % extra cant deficiency (where applicable), are required to certify acceptable running behaviour at a certain maximum permissible speed (or cant deficiency). In the case of the 2008 "Gröna Tåget" tests, the test speed was 275 km/h, or 200 mm cant deficiency in curves, to get the modified Regina with new bogies accepted for 250 km/h and 183 mm cant deficiency. Further tests were done in 290 – 300 km/h on straight tracks, with 303 km/h as a peak speed.

During the tests, the rails were generally dry, with high friction. There is a possibility that lubrication for narrow radius curves (250 – 400 m radii) has influenced the results for 400 – 600 m radius curves, but this can be overlooked in this report as the smallest curve radii examined are 900 – 1500 m.

Test sections

The "Gröna Tåget" tests were done on conventional track sections being used by ordinary trains. By choosing different sections, different kinds of track geometry could be tested. In this analysis three different sections are evaluated: straight track, large-radius curves (R > 2000 m) and medium-radius curves (900 m < R < 1500 m).

For tests on straight track the 38 km long double track between Skövde and Töreboda was used. This track section has some interesting aspects: the Up-track and Down-track have very different characteristics, which are summarised in Table 4-1.

Table 4-1 ***Skövde – Töreboda straight track characteristics.***

	Up-track	**Down-track**
Rail	50 kg/m	60 kg/m
Pad	Stiff	Flexible
Track gauge	1429 – 1434 mm	1436 – 1439 mm

The Up-track is older and built with BV50 rails (50 kg/m) on sleepers with stiff pads, whereas the Down-track is more modern with its UIC60 rails (60 kg/m) on sleepers with quite flexible rubber pads. The way the Up-track is constructed makes the stiffness vary more compared to the Down-track which have an impact on dynamic forces due to the sleeper-passing frequency. The sleeper-passing frequency depends on the speed of the train and the sleeper distance. Over each sleeper the track is stiffer than between them, but with larger rail cross-section and flexible rubber pads the difference in stiffness is smaller. The sleeper distance on these Swedish tracks is 0.65 m, which means the sleeper passage frequency will be 128 Hz at a speed of 300 km/h:

$$f = \frac{v_{km/h}}{3.6l} = \frac{300}{3.6 * 0.65} = 128 \text{ Hz} \tag{3}$$

The tests on straight track were done at two major target speeds: 275 km/h and 290 km/h. The vertical forces filtered with 140 Hz low-pass filter were evaluated at the 275 km/h target speed; whereas the 20 Hz filtered forces were evaluated at both target speeds.

Tests in large-radius curves were done between Örbyhus and Skutskär north of Stockholm. Large-radius curves can generally be negotiated at high speeds, in this case at least 240 km/h. From this test section, the comfort and lateral forces could be interesting in order to see how the train manages to negotiate the curves, especially since the highest permissible speed in Sweden is 200 km/h (there are exceptions where 250 km/h is allowed).

The section with medium-radius curves is the longest and runs from Järna south of Stockholm to Töreboda in the west of Sweden. Curves with medium or small radii cannot be used for high-speed services. On a high-speed line these kinds of curves should not exist, but it is still important to know how trains behave for all kinds of track geometry.

The speed in the test sections with curves depend on the track-plane acceleration, a_y, which is kept within an interval of 1.0 – 1.3 m/s^2. This corresponds to 150 – 200 mm of cant deficiency. In the section with large-radius curves, this generally means speeds around 240 – 270 km/h and in the section with medium-radius curves speeds around 160-170 km/h.

4.1.2 Evaluations

Force evaluation

From the instrumentation on board the train, a number of wheel-rail forces are measured: the track shift forces (S), sliding mean values of the track shift forces, the flange climbing ratios Y/Q, the vertical dynamic wheel-rail forces (Q) and others. Among the listed, the track shift forces, the sliding mean of the track shift forces and the vertical dynamic wheel-rail forces are of interest in this report.

The lateral track shift forces are filtered with 20 Hz low-pass filters and evaluated as a sliding mean over two metres. The amplitudes at 0.15 % and 99.85 % confidence intervals are recorded for both instrumented wheelsets. The 0.15 % and 99.85 % intervals are the value (from zero) at which 0.15 % and 99.85 % of all the collected data can be found. In addition, a sliding RMS value of the track shift forces is evaluated over 100 metres, which move with the train at 10 metre steps at a time.

The vertical forces are filtered with 20 Hz and 140 Hz low-pass filters in order to investigate high-frequency issues, due to unsprung mass and sleeper-passing effects. The 0.15 % and 99.85 % amplitudes of the forces are recorded and in this report the 99.85 % value will be used to investigate the maximum forces. In Table 4-2 below, the limit values for different (measured) forces are shown.

Table 4-2 Limit values for "Gröna Tåget" test train, according to EN14363 and UIC 518.

Force	Limit value
Vertical wheel-rail force Q (99.85 percentile, LP-filtered 20 Hz)	165 kN
Vertical wheel-rail force Q (99.85 percentile, LP-filtered 140 Hz)	No international limit exist
Lateral track-shift force S (or $\sum Y$) (99.85 percentile, sliding mean over 2 metres)	60 kN
Lateral track-shift force S (or $\sum Y$) (99.85 percentile, RMS over 100 metres)	30 kN

Note that no internationally accepted limit for vertical forces with 140 Hz limit frequencies exist. However, in Sweden it is considered that frequencies up to slightly above the sleeper-passing frequency cause track deterioration. An unofficial recommended limit for "track-friendly" trains is currently set to 170 kN.

Comfort evaluation

Comfort is evaluated with Wz (Wertungszahl) and ISO 2631, which quantify the ride comfort (discomfort) of rail vehicles. From the accelerometers described earlier, ride comfort values are calculated in both cars over the bogies and in the middle according to Equation (4) for Wz and Equation (5) for ISO 2631 [3]. The ride comfort is evaluated over 1 km long sections.

$$Wz = 4.42(a^{wrms})^{0.3} \quad (4)$$

where the acceleration is weighted according to Figure 4-2 and a^{wrms} is the RMS value of the frequency-weighted acceleration a^{w}. The weighting function damps out frequencies that are not interesting from a human comfort point of view.

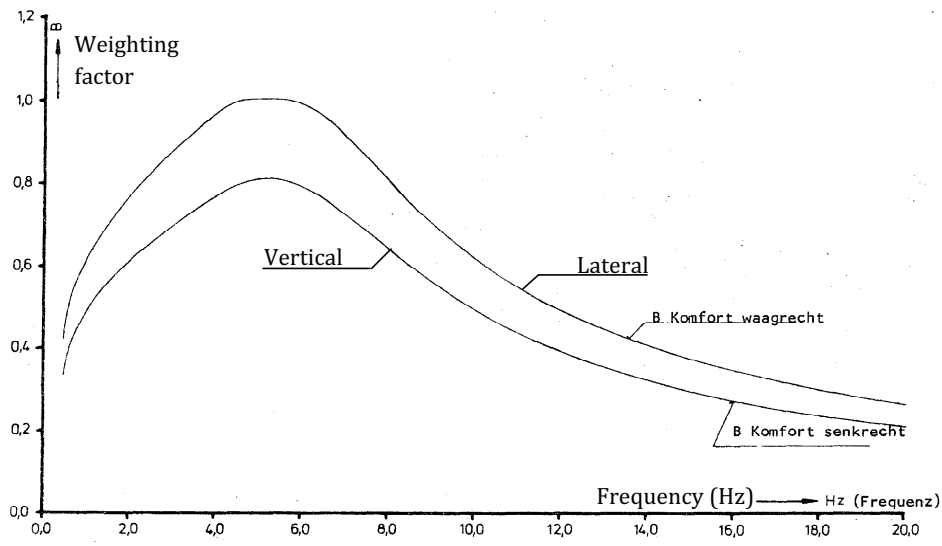


Figure 4-2 ***Frequency weighting curves when calculating Wz.*** *English added in this report, source:* ***[18]****.*

Depending on the results from Equation (4), the ride quality can be determined according to Table 4-3 below.

Table 4-3 ***Wz ride comfort rating.*** *Source:* ***[3]****.*

Wz	Vibration level	Ride quality
1	Just noticeable	Very good
2	Clearly noticeable	Good
2.5	Pronounced, but not unpleasant	-
3	Strong, but tolerable	Tolerable
3.5	Very strong and unpleasant	-
4	Extremely strong and unpleasant	Not tolerable
5	-	Dangerous

ISO 2631 continuous comfort C_c values are calculated from

$$C_C(t) = a^{wrms}(t) = \sqrt{\frac{1}{T}\int_0^T [a^w(t)]^2 dt} \tag{5}$$

where $a^w(t)$ [m/s²] is the weighted acceleration as a function of the time t [s] and T [s] is the duration of the measurement. The accelerations are measured at the floor of the carbody[19]. The weighting functions for vertical and lateral vibrations can be found in Figure 4-3 and Figure 4-4 respectively, where the dashed lines on each side of the weighting curves correspond to the tolerance of the filter. The tolerance is ±0.5 dB inside the frequency range stated in the figure and ±1 dB outside it.

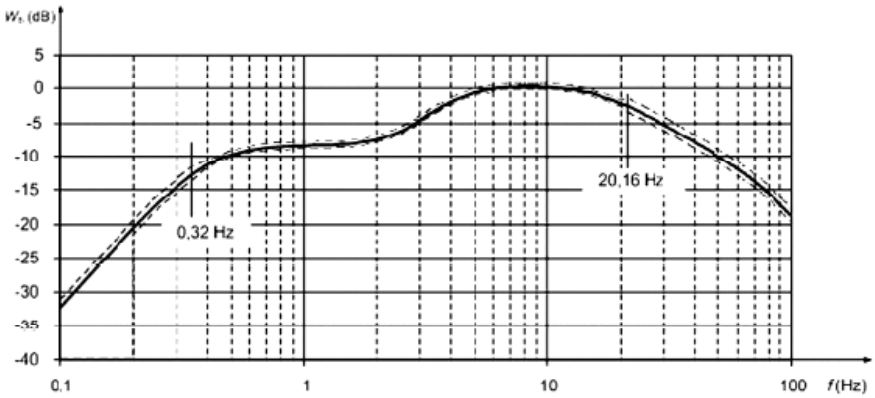


Figure 4-3 ***ISO 2631 vertical weighting curve.*** *Magnitude of the alternative frequency weighting W_b for vertical vibration along the z-axis on the floor, source:* ***[19]****.*

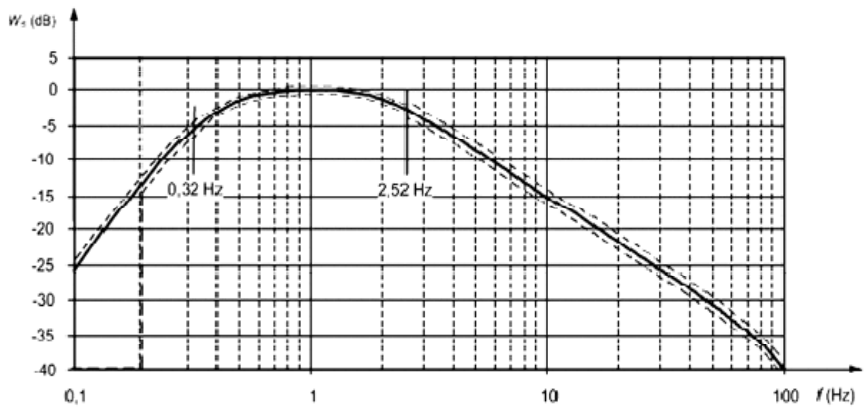


Figure 4-4 ***ISO 2631 lateral weighting curve.*** *Magnitude of the frequency weighting W_d for horizontal vibration along the x- or y-axis on the floor, source:* ***[19]****.*

A scale for judging the ride quality for continuous comfort C_{Cy} and C_{Cz} in the *y*- (lateral) and *z*- (vertical) directions can be found in Table 4-4.

Table 4-4 ***Preliminary scale for the $C_{Cy}(t)$ and $C_{Cz}(t)$ comfort indexes.*** *Source:* ***[19].***

Acceleration range	Ride quality
$C_{Cy}(t)$, $C_{Cz}(t)$ < 0.20 m/s²	Very comfortable
0.20 m/s² ≤ $C_{Cy}(t)$, $C_{Cz}(t)$ < 0.30 m/s²	Comfortable
0.30 m/s² ≤ $C_{Cy}(t)$, $C_{Cz}(t)$ < 0.40 m/s²	Medium
0.40 m/s² ≤ $C_{Cy}(t)$, $C_{Cz}(t)$	Less comfortable

The comfort values from the ”Gröna Tåget” tests are evaluated over each kilometre, which can be compared to Banverket’s standard for track irregularities (BVF 587.02), which suggests a sliding mean of track irregularities over 200 m in the *D1* wavelength range. Due to a more limited amount of ride comfort data, compared to the force data, the ride comfort on straight track is evaluated for the whole speed range of 270 – 300 km/h instead of at the two target speeds described on page 25. When using the two target speeds, some diagrams had too little data for the result to be reliable.

4.1.3 Banverket STRIX track data

The track data from Banverket originates from their track recording car STRIX in July 2008 [20]. This vehicle uses an inertia-based system along with lasers and cameras to measure the relative alignment of the track as well as the rail profile and wear. Any irregularity of the track that exceeds its limit value is marked and a notification is automatically printed.

In Figure 4-5 the schematics of STRIX can be seen. Mirrors guide two laser beams that, together with a camera, are used to measure the track gauge. Two position sensors measures the distance from the wheel axle to the carbody, where two accelerometers are mounted. Together they record the vertical irregularity of each rail. The accelerometers are mounted on the carbody to avoid too much high-frequency noise in the signals. The lateral alignment of the track is recorded by the same lasers that measure the track gauge together with an accelerometer mounted on the same frame as the lasers.

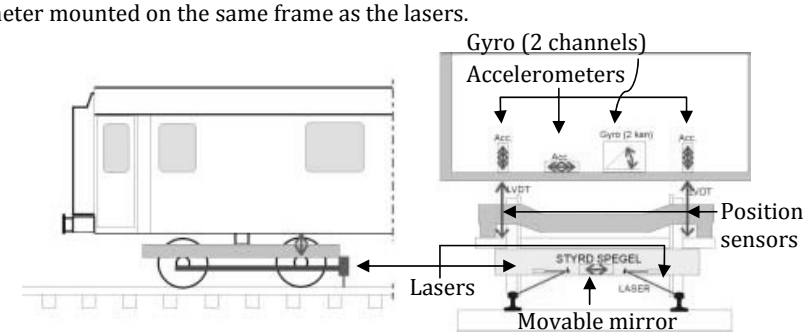


Figure 4-5 ***STRIX components.*** *Arrows and text added in this report, source: Banverket* ***[21]****.*

The signals from the measuring system contain information about the relative vertical and lateral alignment, track gauge, cant and curvature and in addition the track twist is calculated from the earlier mentioned parameters. The results are recorded each 0.25 m. The data is then filtered, stored and displayed on the on-board computers. There is also a possibility to upload the data via Internet to a main server.

The wavelength ranges that were chosen for the work in this report are 1 – 3 m, 3 – 10 m, 10 – 25 m, 25 – 70 m and 70 – 140 m. As was mentioned in Section 2.3, the 1 – 25 m range needs to be divided into narrower wavelength ranges. The Swedish standard [10] defines 1 – 25 m and the European standard [5] defines 3 – 25 m. Hence the 1 – 3 m range is different and is therefore of interest to investigate in particular. The other ranges could be divided more, e.g. 3 – 6 m, 6 – 10 m etc, but the earlier mentioned ranges were chosen as it gives both finer ranges but still not too many alternatives to investigate.

The track data files contain information about position (both internal numbering and actual km points), track quality class, Up-track or Down-track and the track geometry data mentioned earlier [10].

4.1.4 The present Matlab programmes

The Matlab programmes, developed by the author, loads the track data files and the force and comfort data files and matches the test sections' start and stop km-points to km points in the track data, in order to find the correct track section. The wanted test sections are checked manually before running the programme to ensure that no switches or crossings (where the track irregularity signal is discontinuous; see Figure 4-6) will be evaluated. These are not considered being a part of the normal investigated irregularities and might produce inaccurate results.

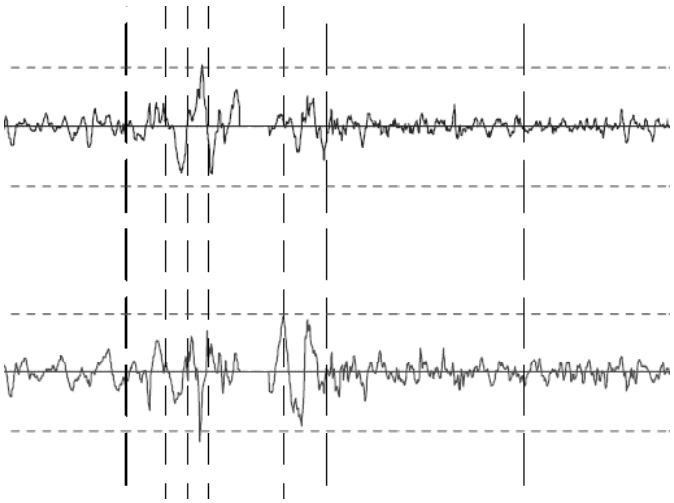


Figure 4-6 ***Example of discontinuous signal (solid lines) for lateral track irregularities.*** *The dashed horizontal lines mark the limit values in BVF 587.02, vertical lines mark km positions, switches, stations and other points of interest. Source:* ***[20]****.*

For vertical forces, only the track irregularities in positive z-direction (downwards, refer to Figure 2-1) are selected by the programme since those are believed to cause the largest dynamic downward force on rails. An upwards irregularity will not produce any significant dynamic force at its maximum amplitude, since the wheel tends to be lifted off the track rather than pushed onto it. A downwards track irregularity will most likely produce a large dynamic force immediately after the passing of its peak amplitude, since the wheel is forced into a different direction (upwards) at that point. However, this assumption will not take the track shape into account or short wavelength defects that might not have amplitudes larger than zero.

Analogically, in curves only lateral track irregularities of the outer rail that points *outwards* from the track centre are selected. On straight track, the mean value of the lateral irregularities for both rails is calculated and used instead.

For the ride comfort, the mean value of the track irregularities from both rails is calculated, since the ride comfort is measured in the car body, which reacts to irregularities from both rails. This applies to both straight track and in curves.

Using the selected track irregularity data mentioned above, the programme then evaluates it over exactly the same section as the force and comfort data in order to estimate the 99.85 % value, mean value and standard deviation for vertical and lateral irregularities, combination (lateral irregularities and cant, see Equation (6) below) and the mean track gauge over 100 metres. Lastly diagrams are plotted for the selected relationships (see Section 4.2 below).

$$s = y_p + h \tag{6}$$

The correlation is calculated from the plotted data sets with Matlab®. Equation (7) shows the general equation for calculating the correlation coefficient R_{xy} for two random and independent variables x and y, where Cov is the covariance and Var the variance [22].

$$R_{xy} = \frac{Cov[x,y]}{\sqrt{Var[x]Var[y]}} \tag{7}$$

R_{xy} ranges from -1 to 1, negative meaning a negative relationship and positive meaning a positive relationship of the regression line.

4.2 Results

Summaries in table form can be found in Appendices C – I for an overview. Because of the massive amount of diagrams obtained by the programme in Section 4.1.4, only some of them will be shown. More diagrams are shown in Appendices J – T. Results with correlation less than 0.4 are usually not shown in Appendix diagrams.

It should also be remembered that even though switches are removed from the track data, bridges still exist. At the ends of the bridges there are often abrupt changes in track stiffness, as well as settlement in the track. Also the track gauge may have abrupt changes. These effects may produce outliers in the diagrams. Outliers produced by a bridge or a large local defect are considered as a normal track irregularity.

Higher correlation is generally achieved by selecting a more specific wavelength range. There is however a possibility that a good correlation between track irregularities in different wavelength ranges increases the correlation between forces or comfort and track irregularities for one or more wavelength ranges. A very brief analysis was made by calculating the correlation between the track irregularities in different wavelength ranges. As suspected, this analysis showed a quite high correlation between the sub-25 metre ranges. An example of this can be seen in Table 4-5.

Table 4-5 ***Example of correlation between different wavelength ranges.*** *The correlation between different wavelength ranges is calculated for the left rail of the Up-track in the test section with straight tracks.*

Straight U track, left rail vertical irregularities, correlation	**1 – 3 m**	**3 – 10 m**	**10 – 25 m**	**25 – 70 m**
1 – 3 m	1			
3 – 10 m	0.65	1		
10 – 25 m	0.52	0.77	1	
25 – 70 m	0.19	0.35	0.45	1

With such a high correlation as 0.6-0.8, the calculated correlations between forces and track irregularities should be compensated. However, as will be seen in the examples below, it will generally not matter as the track irregularity wavelength ranges with the highest correlation stand out sufficiently to still have the highest correlation after compensation is done. No further investigation will be carried out on how the wavelength ranges depend on each other, though this should be remembered when evaluating the results.

4.2.1 Vertical forces (*Q*) vs. track irregularities

The vertical forces are the ones that generally have the highest correlation with track irregularities. Figure 4-7 shows an example with the Q_{11} force, which means the vertical force on the leading axle's left wheel in the travel direction. In the analysis the force Q_{12}, meaning the vertical force on the leading axle's right wheel, has also been available. However, the two vertical forces show similar results, so evaluating one of them is considered sufficient.

Straight track

As shown in Figure 4-7, correlation for the Down-track is very high (0.90), which implies that irregularities in the 3 – 10 metre range are the ones that cause the highest vertical forces, we refer to Appendices J and K for the whole set of diagrams in the ranges 1 – 25, 1 – 3, 3 – 10 and 10 – 25 m for both 140 Hz and 20 Hz filtered forces. The correlation is initially quite high for Q_{11} 140 Hz 1 – 25 m and increases in the wavelength range of 3 – 10 metres. The 10 – 25 m range has a lower correlation than the initial 1 – 25 m range. The 20 Hz filtered forces show a high correlation as well, even higher in the 3 – 10 m range (0.92) than for the earlier mentioned 140 Hz filtered forces, which is most likely due to the lack of high-frequency disturbances (e.g. sleeper passing). For the 20 Hz filtered forces, irregularities in the 3 – 4 m range are filtered out at this speed since they are outside the upper frequency limit:

$$\frac{v_{km/h}}{3.6L} = \frac{274}{3.6 * 3} = 25.4 \text{ Hz} \tag{8}$$

However, this does not seem to affect the result very much, as the correlation in Figure 4-7 is very similar to the results for 20 Hz low-pass filtered forces in the 3 – 10 m wavelength range in Appendix K.

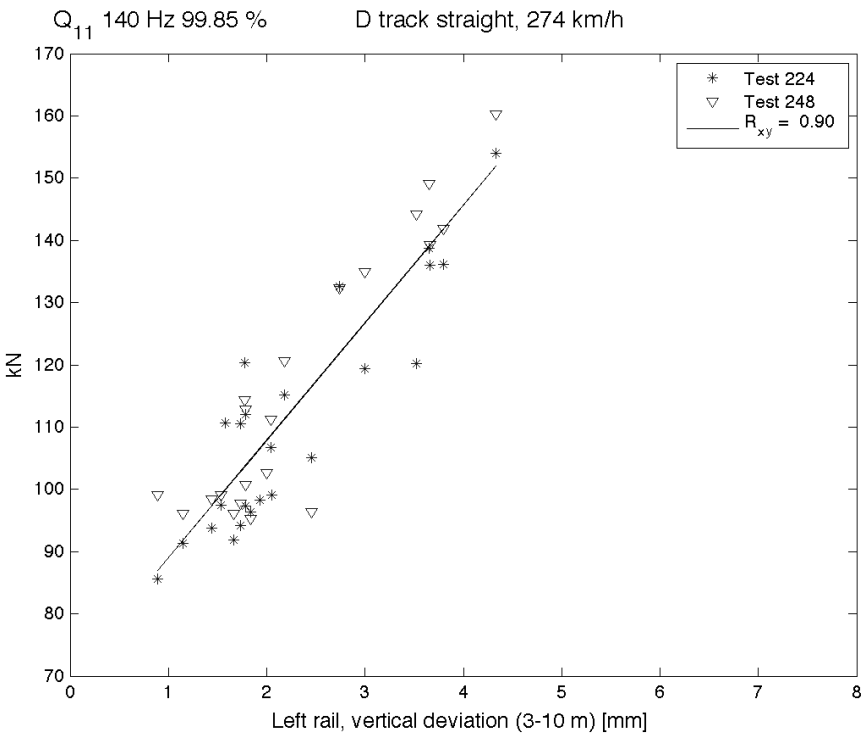


Figure 4-7 ***Vertical forces on the leading left wheel.*** *Down-track, 3 – 10 m wavelengths, 140 Hz low-pass filtering.*

The above example shows a "good" diagram with high correlation, i.e. data are nicely spread around the regression line. There are examples of "bad" diagrams with supposedly high correlation that is achieved by one or two outliers that significantly affect the regression line.

Figure 4-8 (below) is an example of virtually no correlation. Generally the Up-track shows very scattered results, often with low or no correlation, which is probably because there are other circumstances than the track irregularities that affect the results. The sleeper passing and the tight track gauge (1429 – 1434 mm) are undoubtedly two important factors. In particular the sleeper passing produces considerable dynamic contributions to the vertical forces. Sleeper passing on the Up-track causes considerable stiffness variations which result in quite large variations in forces[23]. The tight track gauge causes some sinusoidal motions of the wheelsets at these speeds, also causing some dynamic variations of lateral and vertical forces. Thus there are other causes, occurring independently from track irregularities, for dynamic peaks in measured forces. However, the Up-track is not representative for modern track and thus the results are less important, but still interesting. It can also be noted that the lowest force amplitudes are higher for the Up-track than for the Down-track at moderate track irregularities, which, as explained earlier, is due to the way the track is designed and built.

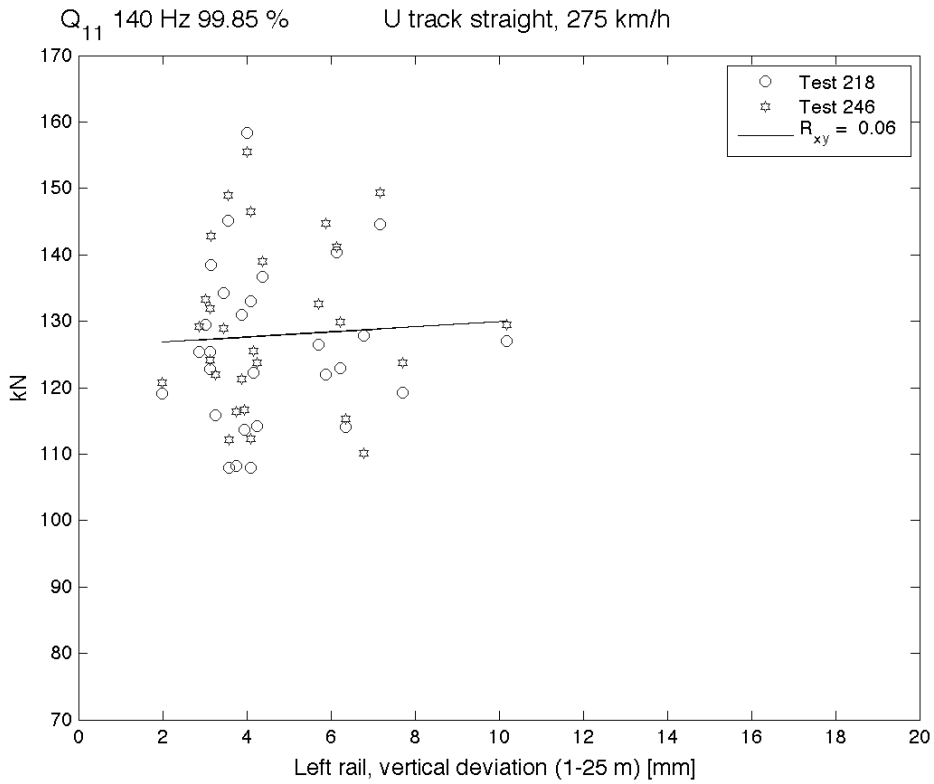


Figure 4-8 ***Vertical forces on the front left wheel.*** *Up-track, 1-25 m wavelengths, 140 Hz low-pass filtering.*

Large radius curves

For curves with large radius it is hard to find any correlation at all. Figure 4-9 shows a typical result for Q_{1X}, where *1X* means the outer wheel of the leading axle in the running direction in the curve. The force is thus always taken from the wheel that runs on the outer rail. The other wavelength ranges can be found in Appendix L, together with 20 Hz filtered forces in Appendix M for reference. Those forces show a very low correlation, similar to the 140 Hz filtered ones.

Note the two rightmost data points in Figure 4-9 that seem to aid in giving a positive correlation. Without those points the correlation would have been lower or even negative (implying that larger deviations would induce lower force amplitudes). One reason for the vague correlation can be that the alignment of the track is very good. Without any variation in the track data, i.e. irregularities that range from none to large, the variation in force amplitude cannot be related to the variation in track irregularity. Instead other causes of force variations produce a scatter in the diagrams.

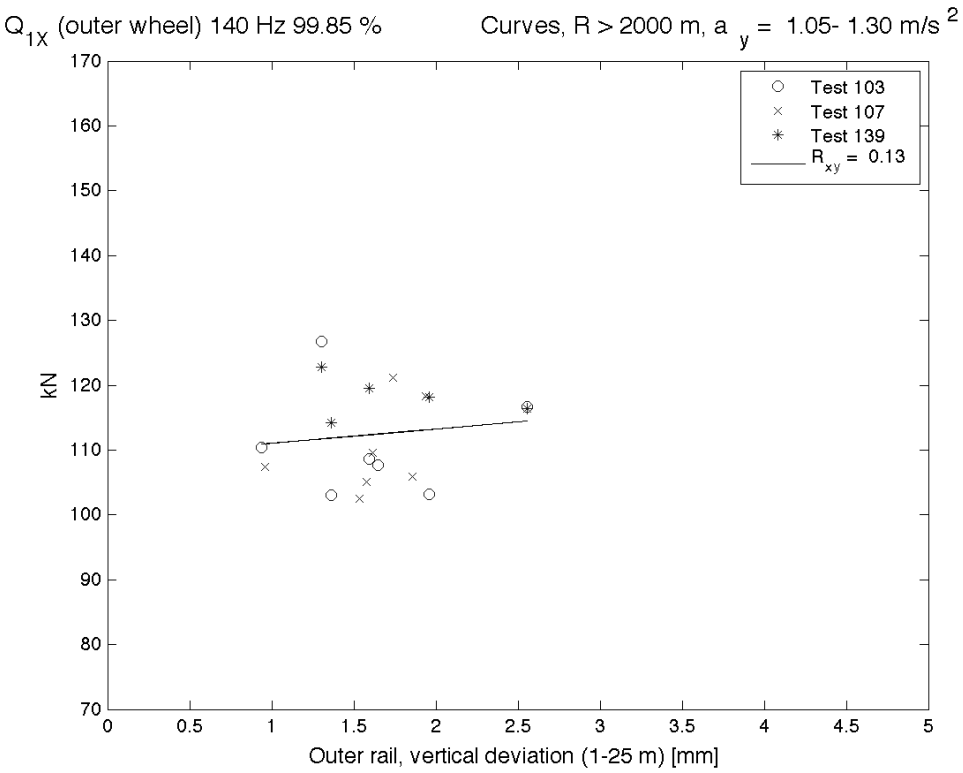


Figure 4-9 ***Vertical forces on the outer wheel in large radius curves.*** *1 – 25 m wavelengths, 140 Hz low-pass filter, the correlation is lower than on straight track.*

Medium radius curves

The results for curves with medium radius are slightly higher than for the large radius curves. This is probably due to the longer distance of this test section, which gives a large variation of track irregularities. Anyhow the correlation must be considered as non-sufficient for establishing firm relationships.

Figure 4-10 shows an example of correlation for medium radius curves. The diagrams in the other wavelength ranges show similar results, except the 1 – 3 metre range which has a higher correlation. However, an interesting aspect is that the 20 Hz filtered forces show a higher correlation than the 140 Hz filtered forces, see Figure 4-10 and Figure 4-11. This may be due to disturbances not filtered out with the 140 Hz filter, for example variations in track stiffness.

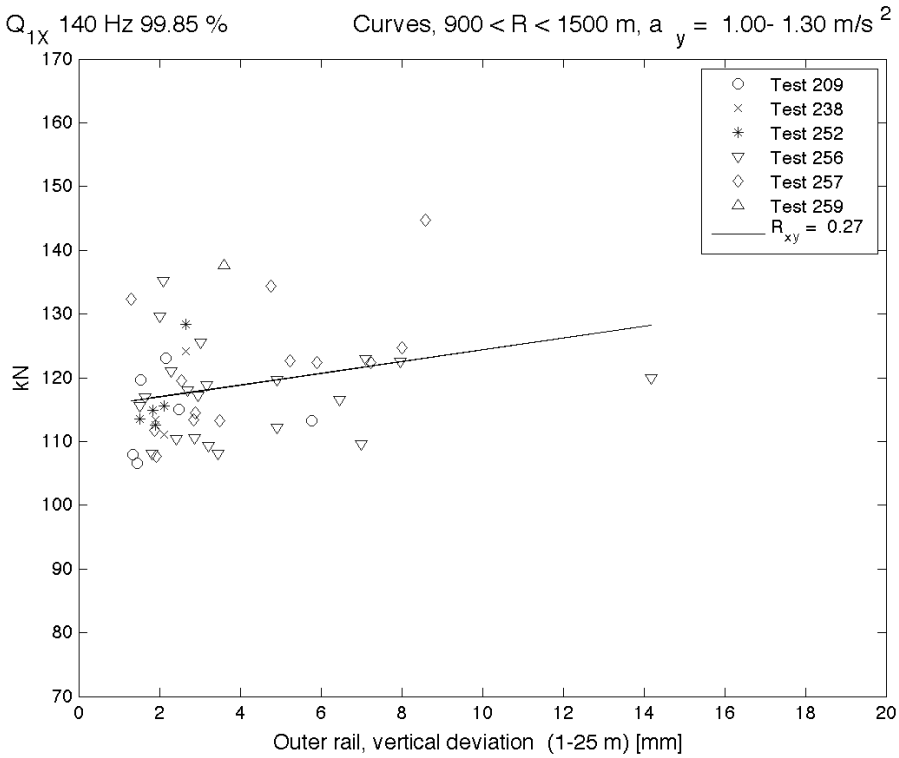


Figure 4-10 ***Vertical forces on the outer wheel in medium radius curves.*** *1 -25 m wavelengths, 140 Hz low-pass filter, the correlation is slightly higher than in the example with large curve radii.*

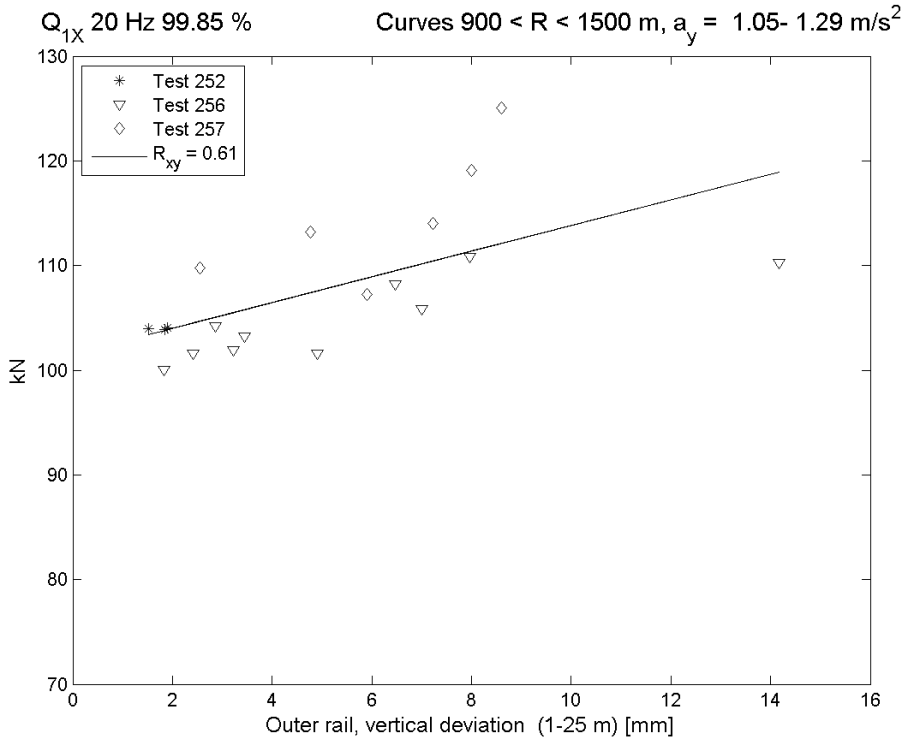


Figure 4-11 ***Vertical forces on the outer wheel in medium radius curves.*** *1 – 25 m wavelengths, 20 Hz low-pass filter, the correlation is higher than with 140 Hz filtered forces. Limit value (EN14363) is 165 kN for this vehicle.*

Diagrams with both 20 Hz and 140 Hz filtered forces and all wavelength ranges can be found in Appendices N – O. The correlation in the 25 – 70 m range for Q_{1X} 20 Hz filter is much higher than the other ranges and it is not clear whether this is by chance or not.

4.2.2 Lateral forces (*S*) vs. track irregularities

The general impression from the analysis of lateral track shift forces is that it is hard to find any clear correlation. Some cases showed better results than others, but nothing was as clear as the vertical forces on the Down-track (Section 4.2.1). Note that S_2 means the trailing axle in the instrumented bogie, not to be confused with the sliding mean over 2 metres, S_{2m}.

Straight track

Finding a very high correlation between lateral track shift forces and lateral track irregularities is not expected on straight track, since the wheelsets usually can run without flange contact. The exception is when the track gauge is very tight, as on the Up-track.

As with the earlier results on the Up-track, the data is extremely scattered. Hardly any relation can be interpreted by looking at Figure 4-12 and the calculated correlation is not zero because there are slightly more data points around 1.5 – 2 mm that "pulls" the regression line down.

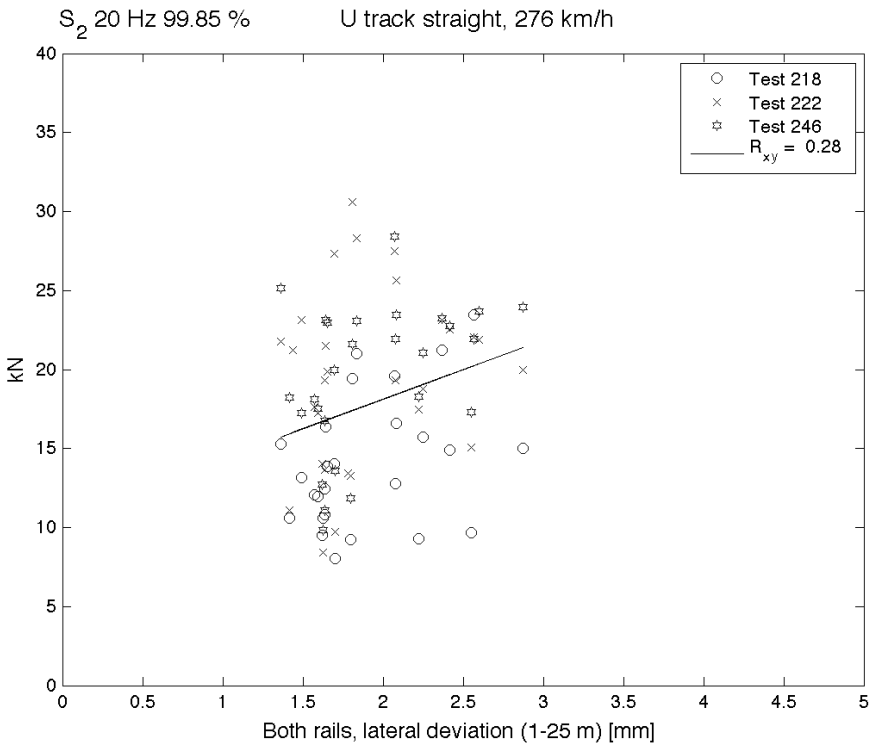


Figure 4-12 ***Lateral track shift forces on straight track (Up-track).*** *Poor correlation between lateral forces and lateral track irregularities when using the 1 – 25 m wavelength range and 20 Hz low-pass filter. Limit value (EN14363) is 60 kN for this vehicle.*

An exception from having higher correlation in wavelength ranges above 25 metre is shown in Figure 4-13, which shows the correlation for lateral forces and lateral track irregularities on the Down-track in the 10 – 25 m range. This example has slightly higher correlation than the above which is mainly due to the more normal track gauge and modern track construction that was mentioned earlier in Section 4.1.1. However, the correlation shown in Figure 4-13 is related to a very limited range of track irregularities between 0.4 and 1.4 mm which makes the correlation uncertain to some extent.

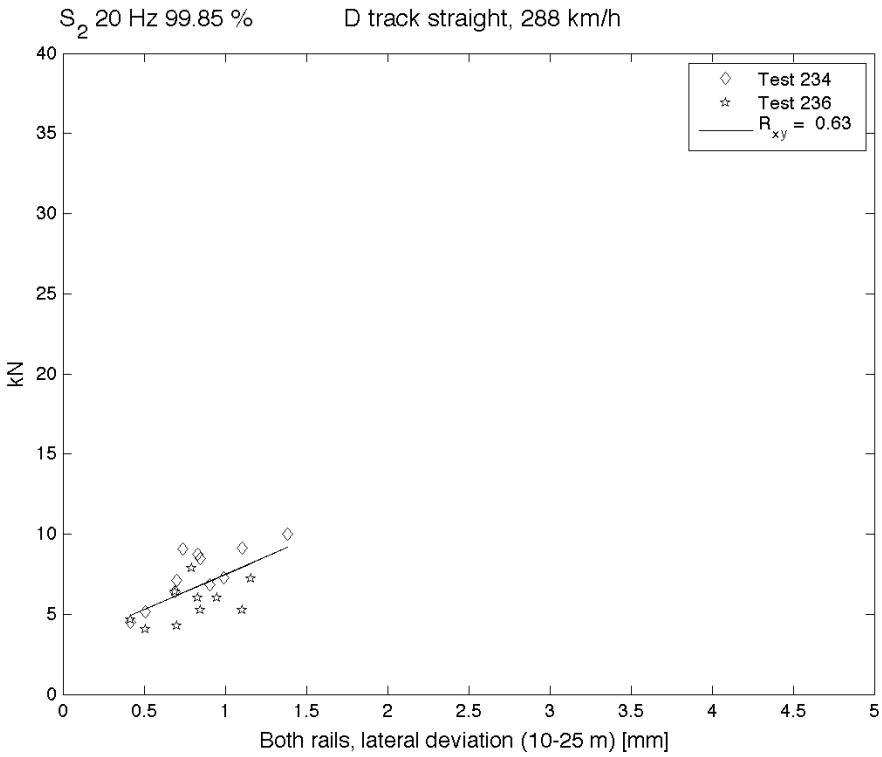


Figure 4-13 ***Lateral track-shift forces on straight track (Down-track).*** *A rather high correlation for lateral track-shift forces and lateral irregularities in the 10 – 25 m range with 20 Hz low-pass filter. Limit value (EN14363) is 60 kN for this vehicle.*

Large radius curves

For large radius curves it is very hard to find any dependence between lateral forces and lateral track irregularities, especially since the track in the zone with large radius curves has a very good alignment. A level of about 30 kN is achieved independently of the actual lateral track irregularities. This level is slightly higher than the quasistatic force for the trailing wheelset at the actual speed and lateral acceleration (cant deficiency). Another explanation is that the bogies have full radial steering through the large radius curves. There is some lateral space between wheel flanges and rails and thus the track irregularities will only have a limited impact on the forces.

The cases with apparently high correlations could simply be achieved randomly. One problem with the large radius curves is the lack of data: it seems as if the results could be evaluated further with more data.

Figure 4-14 shows a slight correlation between lateral forces and lateral track irregularities, but when examining the diagram closer it can clearly be seen that the only reason there is any correlation at all is because of the two rightmost points. Without those the correlation would be closer to zero. Other wavelength ranges show similar appearance and low correlation and thus they are left out.

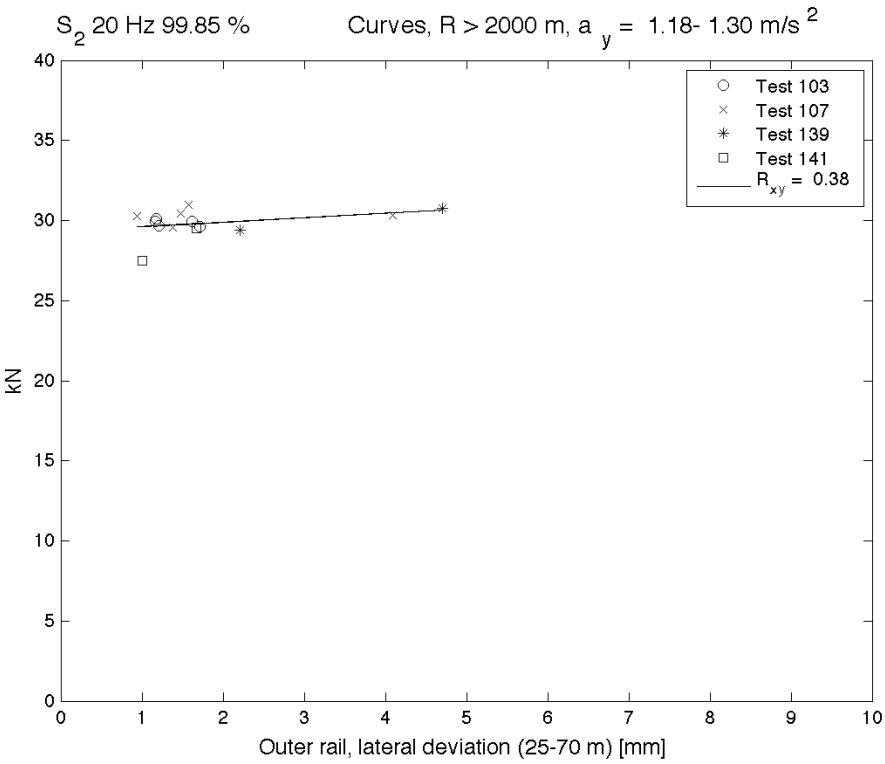


Figure 4-14 ***Lateral track-shift forces in large radius curves.*** *25 – 70 m wavelengths, 20 Hz low-pass filter, the maximum force amplitude does not seem to depend on the lateral track irregularities. Limit value (EN14363) is 60 kN for this vehicle.*

Medium radius curves

For curves with medium radius, the results are similar to the large radius curves. Even though the curve radii are smaller than earlier, it does seem like the lateral irregularities are not affecting the train at all. As mentioned earlier, the train has radial self-steering "soft" bogies. These have full radial steering also through the 900 – 1500 m radius curves. Accordingly there is sufficient lateral space between wheel flanges and rails, which is a possible explanation for the low correlation. Figure 4-15 below is an example in the 25 – 70 metre wavelength range. Other wavelength ranges show similar appearance and correlation.

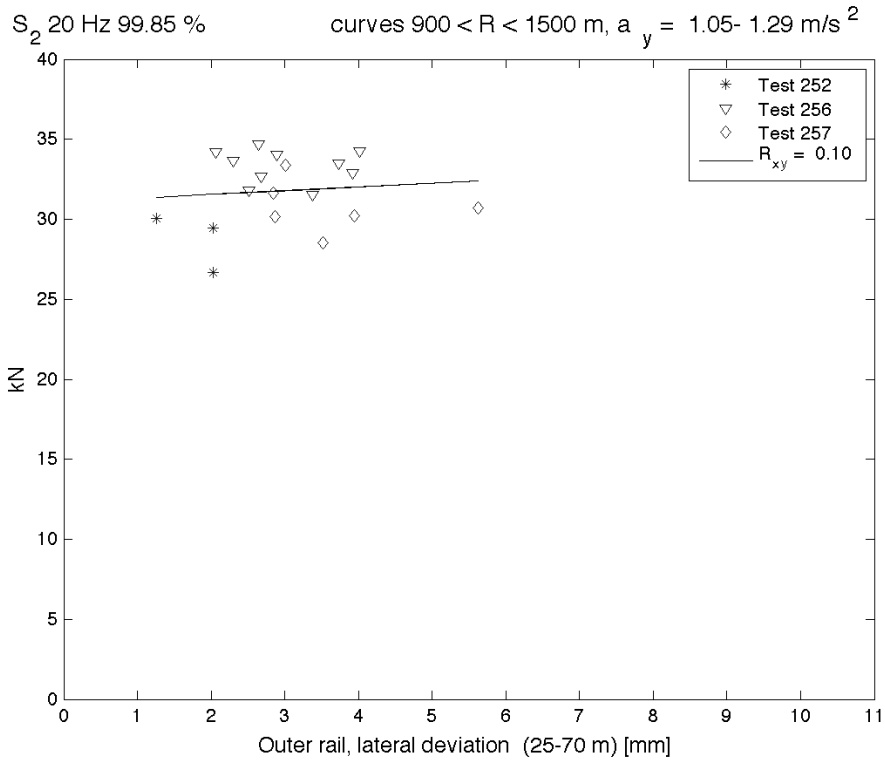


Figure 4-15 ***Lateral track-shift forces in medium radius curves.*** *25 – 70 m wavelengths, 20 Hz low-pass filter, the response is similar to the one in larger radius curves. Limit value (EN14363) is 60 kN for this vehicle.*

Track gauge over 100 metres

The lateral forces in relation to the track gauge over a certain distance, where 100 m is preferred in European standards, show a significant increase in force RMS-values for gauges smaller than 1434 mm. The lateral force in Figure 4-16 is the track shift force for the trailing axle of the instrumented bogie in the travel direction. There are outliers with higher RMS-values than most other points, which could be explained by sudden changes of track gauge over bridges and other local variations.

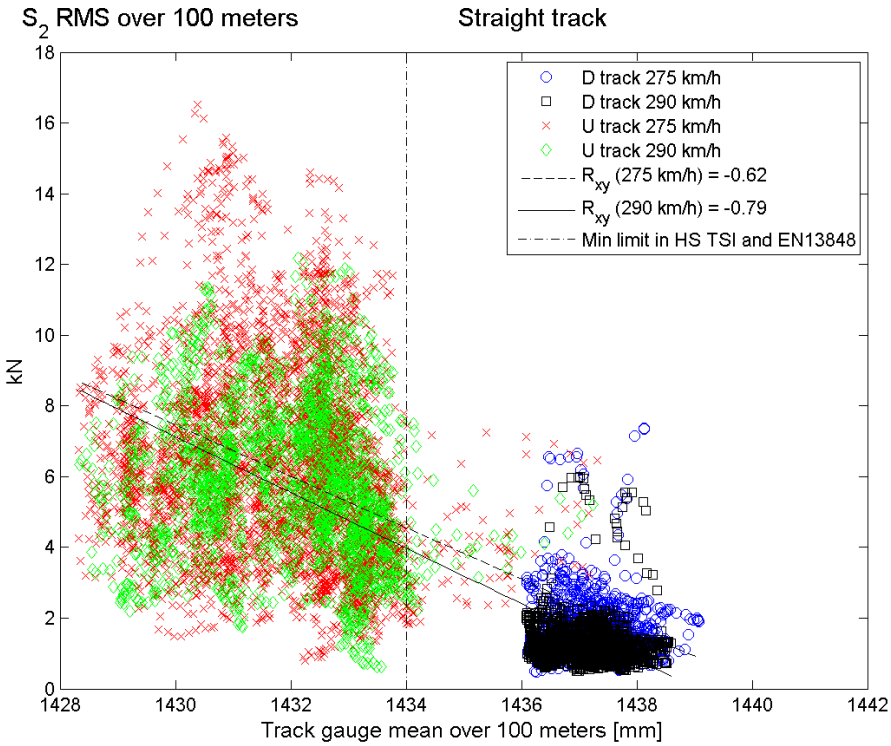


Figure 4-16 ***The RMS of lateral track-shift forces over 100 m in relation to mean track gauge on straight track.*** *Speed indicates the mean speed of the test run, limit value (EN14363) is 30 kN for this vehicle.*

4.2.3 Vertical comfort vs. track irregularities

In general, the 1 – 25 m wavelength range is interesting for vertical comfort since the acceleration filters are the most sensitive between 2 – 10 Hz (see Figure 4-2 and Figure 4-3). However, wavelengths longer than 25 m could be of interest at least for the Wz ride comfort quantification. At 275 km/h, the 1 – 25 m range correspond to 3.1 – 77 Hz:

$$\frac{v_{km/h}}{3.6L} = \frac{275}{3.6 * 25} = \frac{77}{25} = 3.08 \text{ Hz} \tag{9}$$

Similarly to the force evaluation, higher correlation is found vertically than laterally in the ride comfort evaluation.

Straight track

As mentioned in Section 4.1.1, the Up- and Down-tracks are constructed differently. This could be seen fairly clear when evaluating the forces. However, this is not as evident for the comfort results. Vertical comfort results on Up- and Down-tracks are quite equal, therefore results on the Down-track are mainly presented.

Figure 4-17 shows a high correlation, but there are few data points over 1.6 mm. A larger quantity of data points is needed to ensure the accuracy of the results though. One cannot only look at the overview tables in Appendices C – I and draw conclusions without consulting the diagrams. Figure 4-17 and Figure 4-19 are examples of this.

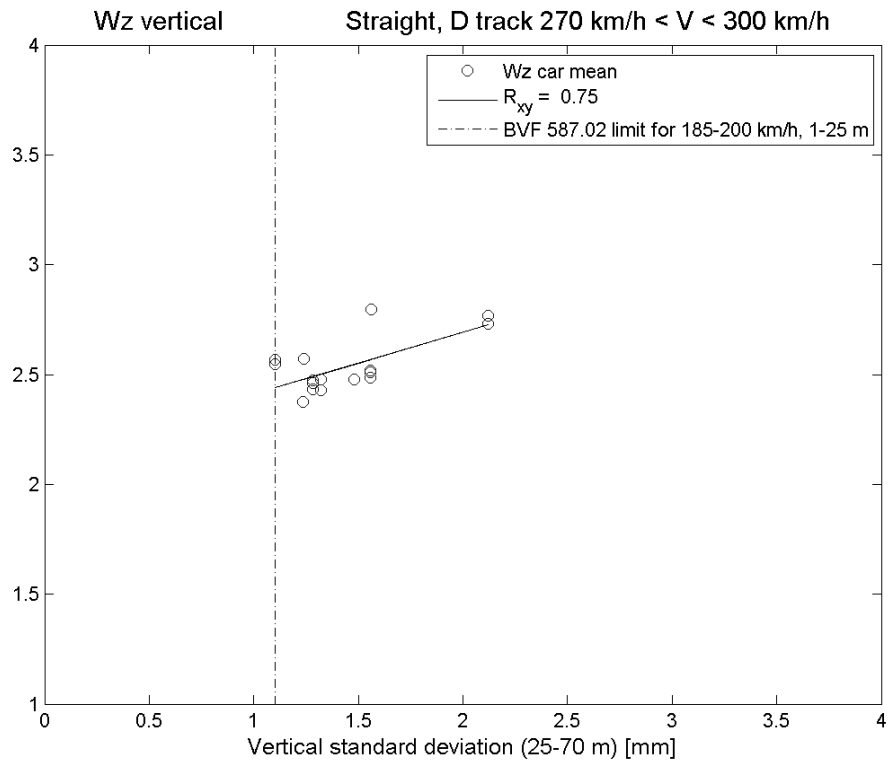


Figure 4-17 ***Vertical Wz ride comfort and standard deviation in the 25 – 70 m wavelength range.*** *Note that the limit value is for the 1 – 25 m range; no limit value for 25 – 70 m wavelengths exist in Sweden today.*

In the vertical direction there is no clear tendency whether short waves (1 – 25 m) or long waves (25 – 70 m) has the highest correlation with comfort. There is a tendency that Wz has a higher correlation in the long-wave range 25 – 70 m, while ISO 2631 has highest correlation in the short-wave range (< 25 m). This is due to the different frequency sensitivity in the Wz and ISO comfort evaluations. This is seen in Figures 4-17 and 4-18 respectively.

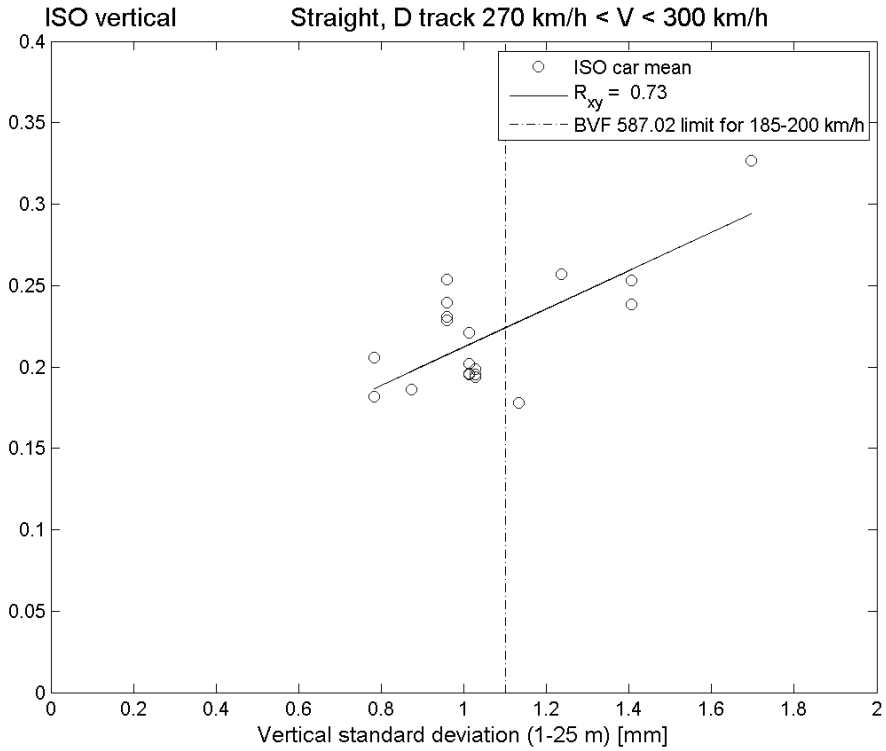


Figure 4-18 ***Vertical ISO 2631 ride comfort and standard deviation in the 1 – 25 m wavelength range.***

Figure 4-19 (very short waves) is more uncertain than Figure 4-18 as there are many points having the same standard deviation (0.12 mm). The 1 – 3 metre wavelength range is also uncertain to judge comfort from, since it is in the upper regions of the frequency ranges of ISO 2631 and Wz (refer to Figure 4-2, Figure 4-3 and Section 4.3). As shown in Table 4-5, there is a correlation between the wavelengths in the 1 – 25 m range that has to be taken into account as well. Refer to Appendices Q and R for ride comfort and longer wavelength ranges.

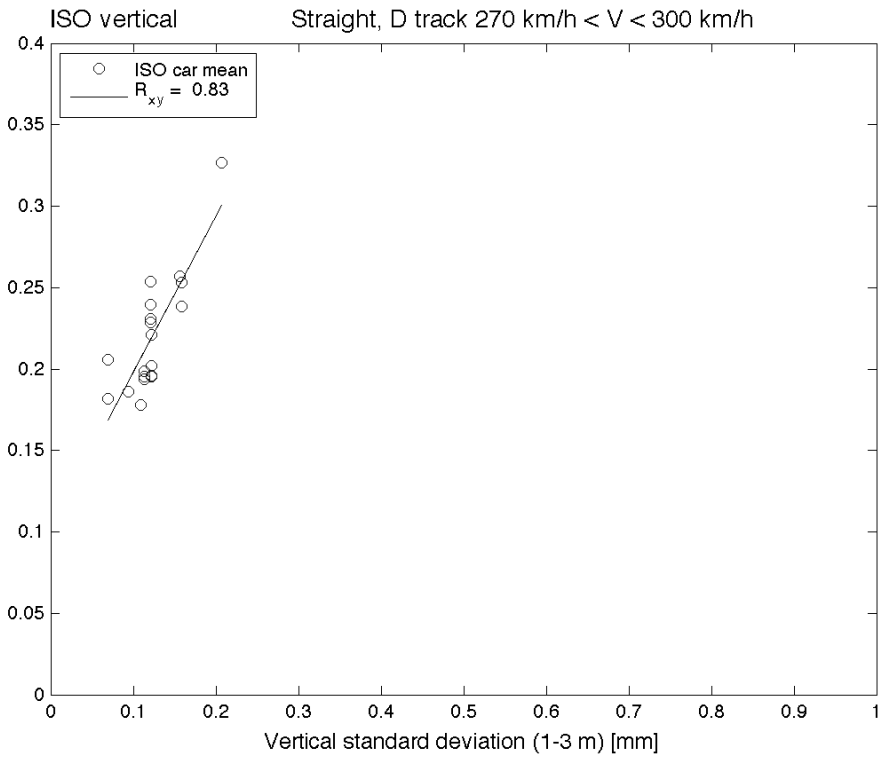


Figure 4-19 ***Vertical ISO 2631 ride comfort and standard deviation in the 1 – 3 m wavelength range.***

Large radius curves

In the curves, there are generally more data which makes the results more reliable than for the straight track. However, the track in the large radius curves is well-aligned which gives little variation in track irregularities. This can be seen in the diagrams for large radius curves by many data points having low standard deviation, although there are some exceptions with larger track deviations.

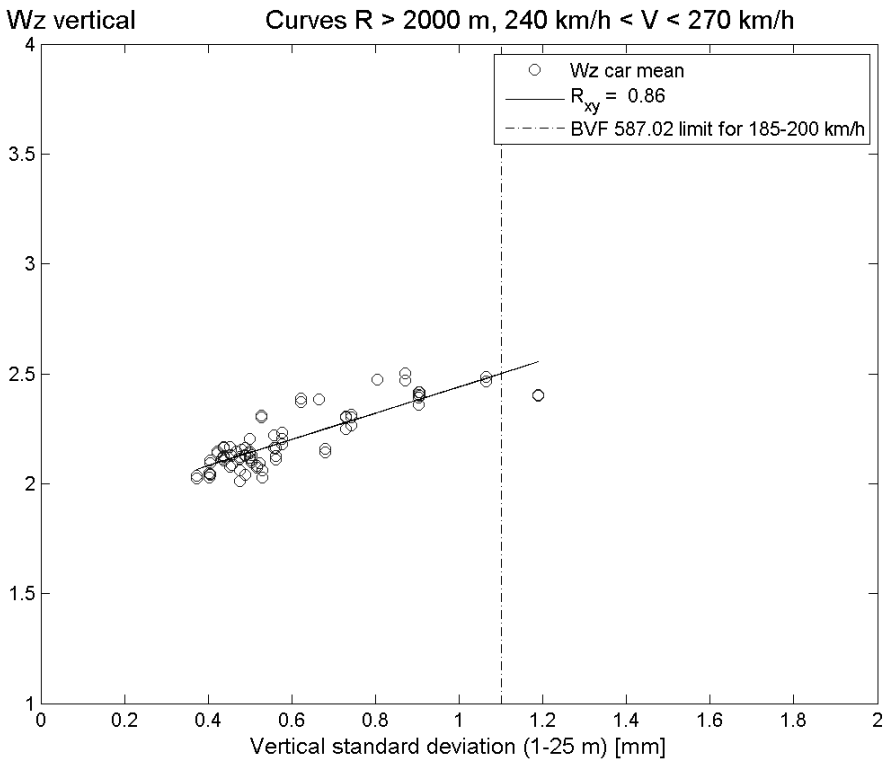


Figure 4-20 Vertical Wz ride comfort and standard deviation in the 1 – 25 m wavelength range.

Figure 4-20 has a high correlation in the 1 – 25 metre range. A high correlation is also seen in the 25 – 70 metre range (see Appendix S), although the relation is not as clear as in the 1 – 25 m range. Judging from the diagram, the vertical comfort has a correlation to the vertical standard deviation of the track irregularities. When evaluating the result using ISO 2631 in Figure 4-21 there is slightly more scatter in the diagram, the same tendency can be seen, however.

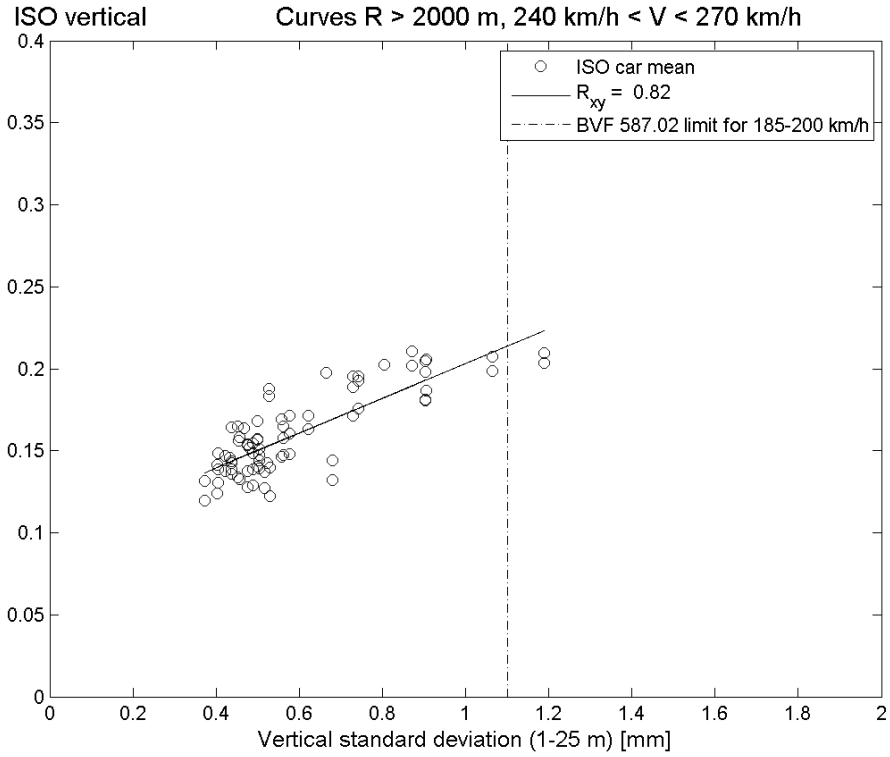


Figure 4-21 ***Vertical ISO 2631 ride comfort and standard deviation in the 1 – 25 m wavelength range.***

Medium radius curves

For the medium radius curves, the results are similar to the large radius curves but with much more data and statistically better track irregularity data scatter. The longer total length of this test section gives more data to evaluate, as can be seen in Figure 4-22.

The high correlation in Figure 4-22 suggests that there is a strong connection between vertical comfort and standard deviation of vertical track irregularities. The ISO 2631 diagram (see Appendix T) has a slightly lower correlation, but still shows a strong relation between vertical comfort and this standard deviation.

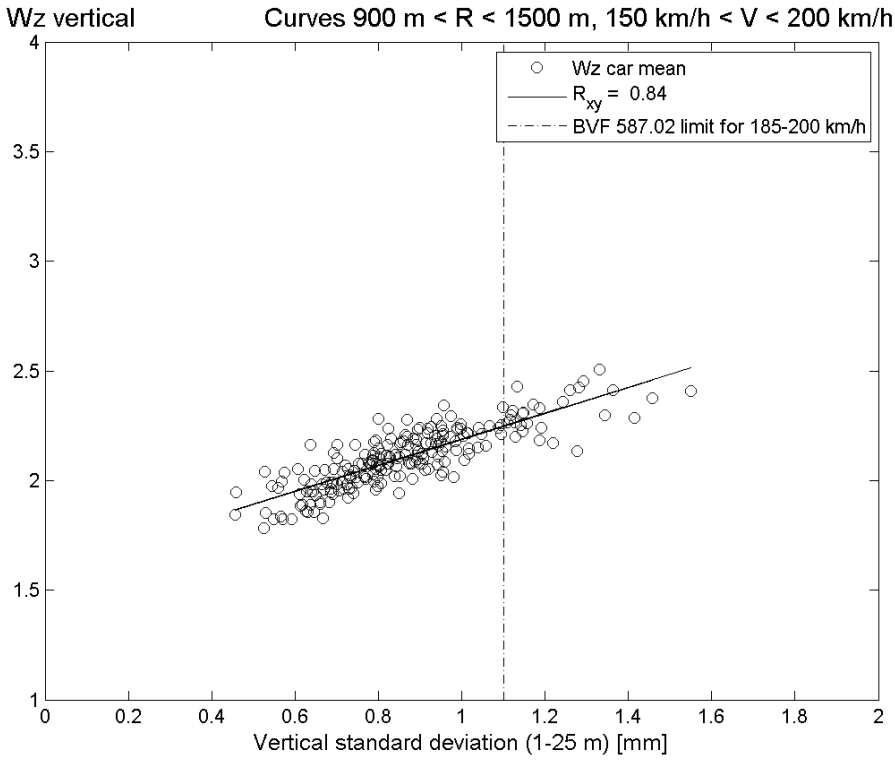


Figure 4-22 Vertical Wz ride comfort and standard deviation in the 1 – 25 m wavelength range.

4.2.4 Lateral comfort vs. track irregularities

For lateral ride comfort quantified by ISO 2631, wavelengths longer than 25 m is of most interest because of the weighting filter's cut-off frequencies (see Figure 4-4). At 275 km/h, the 25 – 70 m wavelength range corresponds to 1.1 – 3.1 Hz:

$$\frac{v_{km/h}}{3.6L} = \frac{77}{70} = 1.10 \text{ Hz} \tag{10}$$

$$\frac{v_{km/h}}{3.6L} = \frac{77}{25} = 3.08 \text{ Hz} \tag{11}$$

The weighting filter for Wz laterally, however, reacts to the same frequencies as vertically (2 – 10 Hz, see Section 4.2.3).

Straight track

Laterally, the relation between comfort and standard deviation is not as clear compared to the results vertically. Although the highest (absolute) correlation for Wz is achieved when filtering the track data in the 3 – 10 m wavelength range, this can be discarded as a random result, since all comfort values essentially have the same standard deviation (0.3 mm). This means the track irregularities do not vary enough within the wavelength range to produce a reliable relationship between lateral comfort and lateral track irregularities. Without any variation of the standard deviation in the track data, no relationship can be tendency can be seen between track irregularities and comfort data.

For longer wavelengths, the result for lateral Wz is not very convincing (see Appendix R); a vague relation can be seen. If the diagrams in the same wavelength ranges for ISO 2631 are inspected, the results are much clearer: short wavelengths up to 25 metres show a very low correlation, but longer wavelengths show a high correlation (see Appendix R for these diagrams). This is probably due to that ISO 2631's lateral filter, which respond more to low frequencies, compared to the lateral filter for Wz.

The relation is clearer on the Down-track than on the Up-track, especially for longer wavelengths, as can be seen in Figure 4-23. The more clear relation is a result of fewer disturbances from the tight track gauge and older track design on the Up-track. However, due to the few number of observations, the found relation may be randomly achieved.

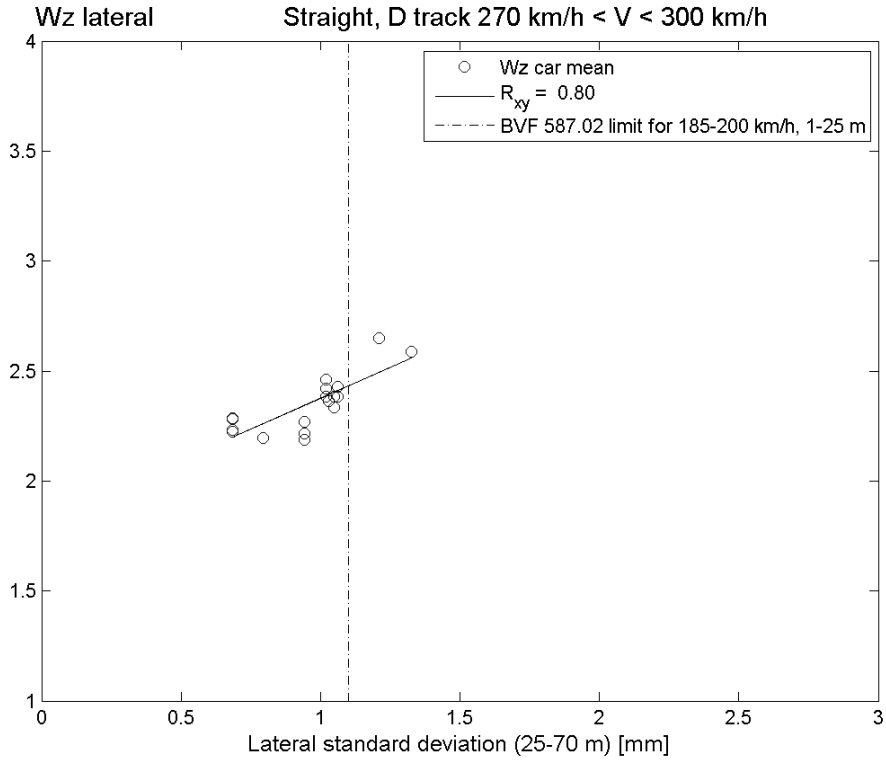


Figure 4-23 ***Lateral Wz ride comfort and standard deviation for 25 – 70 m wavelengths.*** *Note that the limit value is for the 1 – 25 m range; no limit value exist for 25 – 70 m wavelengths in Sweden today.*

Evaluating comfort with the standard deviation of lateral and cant combination shows similar results as lateral standard deviation. This is most likely connected to the way combination is calculated (see Equation (6)): with lateral and cross level irregularities. The cross level irregularities are small on the straight track, which means that the combination is very similar to the lateral irregularities.

The lateral comfort can be evaluated as a function of the track gauge to determine how track gauge will affect the comfort. Figure 4-24 contains data from both the Up-track, with tight track gauge, and the Down-track, with wide track gauge. For the straight track in Figure 4-24, it seems as if the tighter track gauge gives higher accelerations in the carbody and thus worse comfort.

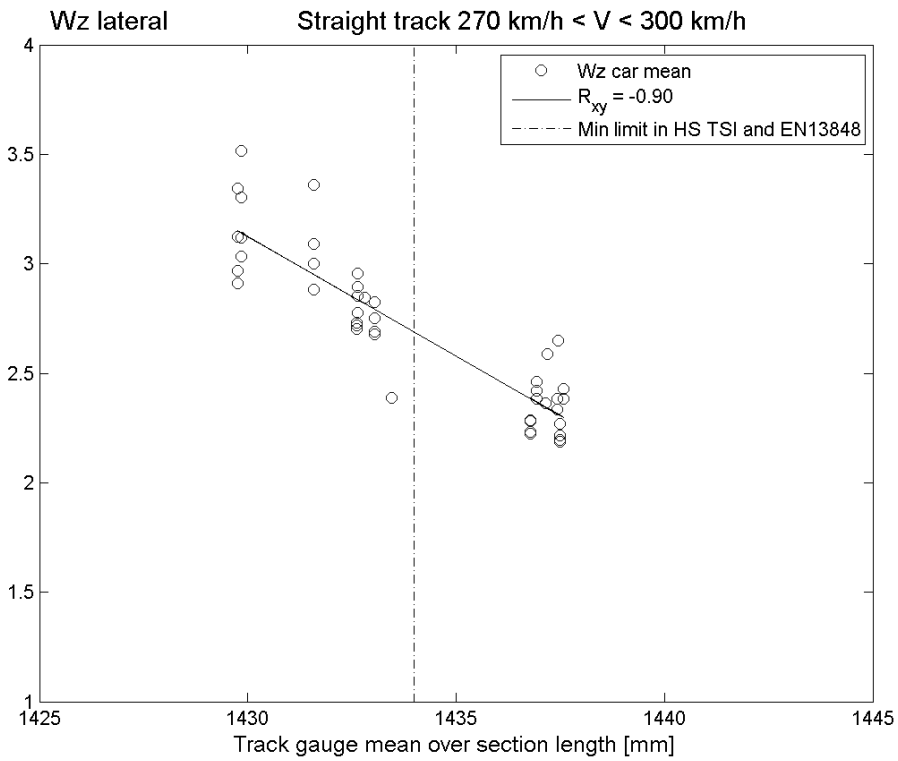


Figure 4-24 ***Lateral Wz ride comfort and track gauge mean over the 1 km comfort sections on straight track.*** *The limit value corresponds to the HS TSI and EN13848 limit for mean track gauge over 100 m for speeds over 230 km/h.*

Large radius curves

An issue that can be seen in all diagrams from the large radius curve section is the concentration of data points around low standard deviation values. This often makes the diagrams hard to evaluate, resulting in very low correlation. No clear relations between lateral deviations and lateral comfort can be found.

Evaluating lateral comfort with lateral and cant combination gives occasionally a quite high correlation, as can be seen in Appendix H. However, a detailed study shows that the correlation is achieved by chance, due to a very limited number of observations. The data needs more variation in order to draw reliable conclusions.

Medium radius curves

The results for medium radius curves much follow the results for large radius curves, but have more data and thus are more reliable. Complementary diagrams can be found in Appendix T. In Figure 4-25 the same issue as for large radius curves can be seen: many data points at low standard deviation. But, due to the more extensive amount of data, the variation is fairly good. The diagram shows a quite strong connection between lateral track quality (measured by standard deviation) and lateral comfort.

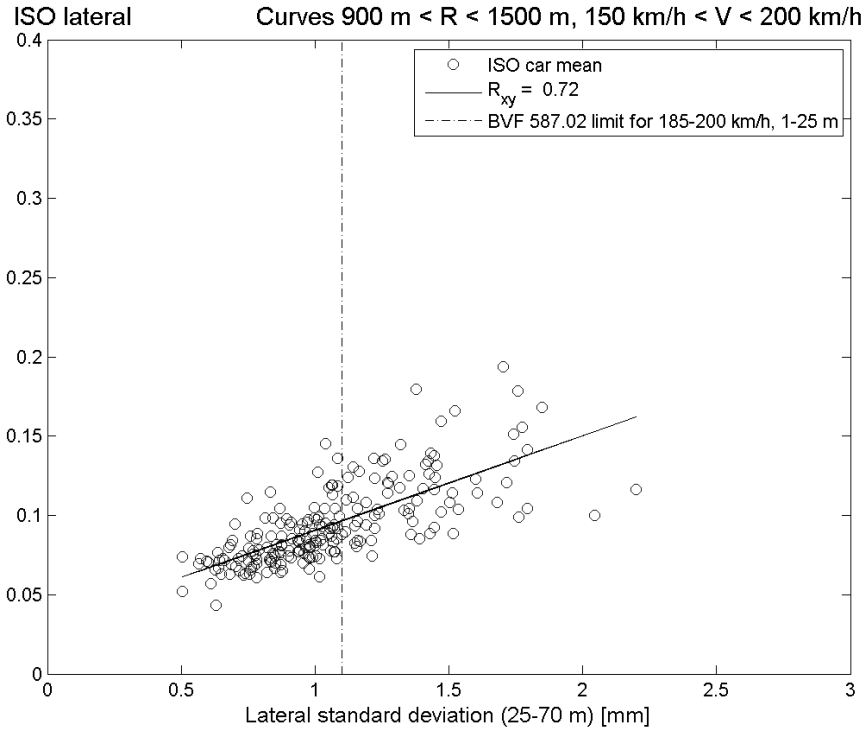


Figure 4-25 ***Lateral ISO 2631 ride comfort and standard deviation in the 25 – 70 m range.*** *Note that the limit value is for the 1 – 25 m range; no limit value for 25 – 70 m wavelengths exist in Sweden today.*

The diagrams showing lateral comfort related to lateral and cant combination look similar to the ones for large radius curves and can be found Appendix T for reference. The correlations are about the same as for the previous cases with pure lateral deviation.

There is no clear relation between lateral comfort and track gauge in curves.

4.3 Discussion

When evaluating the results in this report, it is important to keep in mind that they are only based on one type of train: the Regina test train. Some aspects that might affect the results are related to the train type itself, especially since the Regina train is designed for speeds up to 200 km/h. There are also some issues with the tracks where the tests were done: the section with straight track has different designs (which were discussed in Section 4.1.1) and the large radius curves seem to be too well-aligned for the scope of this study. Especially the lateral alignment of the track is very good, in particular in the large radius curves. This results in a low variation in the track data and gives a chance for other parameters to affect vehicle running behaviour and response. This issue is discussed further in each of the sections 4.3.1 – 4.3.3 below.

Some results for vertical forces show a high correlation in the 1 – 3 m range, which could involve grinding the track (for the shortest wavelengths) rather than aligning a longer section. Judging track quality solely from this short wavelength range will most likely result in longer wavelength errors being missed out at the track inspection and evaluation. Hence, also longer wavelengths must be included.

It is easy to look at the tables in Appendices C – I that summarize the results in order to get a quick overview over what wavelength ranges and responses having the highest correlation. But, as mentioned earlier, it is important to also study the diagrams in order to draw correct conclusions: a high correlation coefficient *could* mean that an important relation exists, but it could *also* mean that there is only limited relation and the high correlation coefficient is caused by chance. This can be seen in Figure 4-19 for example.

4.3.1 Straight track

Results for the straight track are very different when comparing the present Up-track and Down-track. The Up-track design is older and not very representative for a future high-speed track, whereas the Down-track is of a newer type (Section 4.1.1). The results from the Up-track are interesting because of the tight track gauge that provides a high equivalent conicity. The conicity is measured to be up to 0.8 on some sections, instead of max 0.3 as specified in UIC 518 and EN14363. Therefore the Down-track is more interesting, as it is more representative for a modern track. In addition the vertically stiff track, in combination with the quite weak rails, produces more or less continuous dynamic force variation due to sleeper passing.

What can be seen from the difference between the Up-track and Down-track is that a too tight track gauge is not favourable. At speeds over 270 km/h there is a significant increase in track-shift force amplitude for mean track gauges less than 1434 mm, as well as worse comfort although the levels are below present limit values. It can be noted that the maximum force amplitudes still are only about half of the recommended limit in UIC 518 and EN14363, and that these levels are achieved when running at more than 270 km/h on a track designed for 200 km/h. The recently developed and improved soft bogies of the test train are most likely the reason for the low force amplitudes, despite of this track. It should be noted that the new EN also recommends that the track gauge should not be tighter than 1434 mm for speeds higher than 230 km/h.

Another issue worth noting is that the lateral irregularities do not seem to affect the lateral forces very much. This could be explained by that the bogie and the wheelsets absorb most of the lateral irregularities with its laterally and longitudinally soft primary suspension. On the Up-track there are more parameters involved, especially the tight track gauge which gives a slightly sinusoidal running behaviour.

Laterally the correlation between ride comfort values and standard deviation of the track irregularities are high in the 25 – 70 metre or 25 – 140 metre ranges. This is in particular so for the ISO 2631 filter. The occasionally high correlation in the 1 – 3 metre range could be affected by the nearby 3 – 10 m or 10 – 25 m ranges, as shown in Table 4-5. These relationships are quite uncertain due to the limited number of observations and data.

Vertically a high correlation can be found between vertical forces and isolated defects on the Down-track. As discussed earlier, the Up-track exhibits aspects that make responses from track irregularities hard to correlate to the actual track irregularities. Similar results are received from the evaluation of comfort values and standard deviations, although the results from the Up-track are not as diffuse as in the force evaluation. Generally the vertical irregularities have sufficient variation to provide accurate results and imply that there is need for stricter track quality limit values at speeds of 250 km/h and above.

4.3.2 Large radius curves

Results from the test section with curve radii over 2000 metres are not very clear. This is mainly due to three issues: a small amount of data, very well aligned track as well as vehicle motions not induced from track irregularities.

With a track that is well aligned, with a few exceptions, there will only be small variations in the track irregularities and thus hard to see what the resulting vehicle response will be. As shown in both Figure 4-9 and Figure 4-14, the correlation is very low. When looking at the standard deviations vertically and laterally, there are many data points having similar standard deviation, meaning there is little variation in the amplitude of the track irregularities.

Another aspect of the low variation in track irregularities is that the test train's soft bogies can self-steer through curves without flange contact. Thus the lateral irregularities may be too small to affect the running behaviour of the train significantly and, as stated earlier, other issues will be affect the vehicle response.

More general results could be received by investigating also other vehicle types, with different running behaviour, on a track with more variation in track irregularities. This is typically done by simulating the same track for different vehicles and will result in a larger quantity of data for evaluation.

4.3.3 Medium radius curves

Much of the issues discussed for the large radius curves can also be applied to the medium radius curves: the radially steering "soft" bogies producing just a modest response to the track irregularities. However, in medium radius curves there are more data to draw conclusions from, thus increasing possibilities of more accurate result. Generally some influences from the track irregularities are shown.

4.3.4 How representative is the "Regina" test train for future high-speed trains?

The "Gröna Tåget" test train is a modified Bombardier Regina train (see Section 4.1.1), which is designed for a maximum permissible in-service speed of 200 km/h. Since the carbody in the Regina train set is not made for travelling at 300 km/h it shows some vibrations or oscillations that a new very-high-speed train will presumably not show. Thus, the comfort, in particular vertically, in a future high-speed train will probably be better than in the Regina test train.

High-speed trains traditionally have very "stiff" bogies, in contrast to the "soft" bogies (see Section 3.1.1) of the test train. Stiff bogies have a stiff primary suspension longitudinally and laterally and thus allow very little horizontal movement of the wheelsets relative to the bogie frame. Having stiff bogies have long been considered as an advantage, since the critical speed before start of hunting is often related to the stiffness of the primary suspension and wheelset guidance [3]. But a stiff bogie has worse curve negotiation than a bogie with softer primary suspension. The new developments of the test train have shown that improvements are possible also with the less stiff bogies.

Table 4-6 shows a comparison between the running characteristics of the Regina test train in comparison with an average European high-speed train.

Table 4-6 ***Running characteristics of the Regina test train as compared with an average European high-speed train.*** *Estimates by professor Evert Andersson, KTH Rail Vehicles.*

Vehicle response	Regina test train
Vertical track forces	About equal or slightly better
Lateral track forces	Better
Vertical comfort	Worse
Lateral comfort	About equal

A "soft" bogie produces a better distribution of the track-shift forces between the wheelsets that lowers the risk for track shifting [3]. "Soft" bogies also produce lower dynamic contribution in the lateral direction.

Another aspect of the test train's four bogies is that two of them are equipped with active lateral suspension (ALS). The ALS improved the lateral comfort by cancelling out movements that would otherwise have a negative impact on the comfort. However, this technology is not something one can assume that every high-speed train is equipped with in the near future, although it is likely to be implemented more frequently where the need is large, in particular when running large-radius curves at high cant deficiency. This is why the lateral comfort data was taken from the car without ALS, as was mentioned in Section 4.1.1. Note that the vertical comfort data and the forces are measured in the car that features ALS.

It is advisable to investigate other train types and tracks as well, preferably trains with "stiffer" bogies, in order to achieve more general results.

5 Conclusions, recommendations and future work

This part contains conclusions and recommendations based on the present work as well as suggestions on future work.

5.1 Results achieved in the present study

In the present study a particular test train – the modified "Regina" train – is studied on a number of types of tracks and track geometries. The selection of tracks was made mainly for the purpose of certification and compliance to UIC 518 or EN14363, to a large extent at speeds lower than or up to 200 km/h. Available test data were in some cases not ideal for the purpose of this study.

Nevertheless it was possible to establish some relationships between track geometry and vehicle response, both regarding track forces and ride comfort, in particular in the vertical direction. In some cases however, these relationships are uncertain and should be subject to further investigations.

5.2 Conclusions on track quality

Some general preliminary conclusions drawn from the evaluations are:

- The lateral limit values in BVF 587.02 *are* likely strict enough for higher speeds
- The vertical limit values in BVF 587.02 *are less* strict and may be tightened for higher speeds
- Lateral and cant combination differs very little from lateral irregularities in the investigated cases
- A lower limit for mean track gauge over 100 metres must be part of future standards for high-speed tracks.

These are conclusions that can be drawn directly from the results presented earlier, where it can be seen that the lateral track quality is good whereas the vertical track quality needs some improvement. There are two more conclusions:

- The limit in the European High-Speed TSI or EN13848 for track gauge over 100 m seems reasonable (i.e. min 1434 mm at speeds ≥ 270 km/h)
- The necessity of requirements on lateral and cant combination as well as track gauge change over 10 m should be further considered.

Judging from Figure 4-16, the limit values on track gauge as stated in e.g. the High-Speed TSI or EN13848-5 are very reasonable.

5.3 Recommendations

No specific recommendations can currently be made about track quality limits. However, some general aspects have been discussed in this report which involve that:

- The definition of the quality levels has to be stricter and more clear
- New track quality levels could follow the international standards AL, IL and IAL, instead of the current B, C and "risk for derailment"
- The vertical limit values have likely to be stricter at higher speeds
- Track gauge mean over 100 metres must be included in a new standard.

BVF 587.02 should have stricter quality levels. Now level B is forcing maintenance only to a limited degree, even though tracks should not become as poor as level B before the next normally scheduled maintenance. Thus a level B error should require maintenance of the section in question at the next scheduled maintenance occasion. Also more strict rules for immediate action due to safety should be considered.

5.4 Future work

To achieve a more general perspective more work needs to be done. The current results are based on on-track tests done with a modified "Regina" train, which cannot represent the wide selection of trains that exists and will exist in the future. In order to improve this research, the following is suggested:

- Multibody dynamics simulations
- Differentiation of irregularities
- Make PSD graphs
- Use more data from later tests
- Test of alternative track evaluation criteria

The most important points are the first three.

Simulating different vehicles over the same track section will give more general results. Systematically changing track parameters will give a better understanding of how track irregularities affect track forces and ride quality.

By evaluating track irregularities by means of their spatial derivatives, it would be possible to find correlation or information where the method used in this report (e.g. isolated defects, mean values, standard deviations) has failed.

Making both track irregularity and vehicle response PSD, power spectral density, diagrams can show at which frequencies the response is high, i.e. if any particular frequency stands out more than another, which can be used to find a particular wavelength where track irregularities cause high forces or poor ride comfort.

By using data from tests done after the summer of 2008, the need for track irregularity variation discussed earlier can be considered. But there is a risk that the results turn out similar to the ones in this report and this option should therefore have low priority.

6 References

[1] CEN, *EN13848-1:2003+A1:2008 Railway applications - Track - Track geometry quality - Part 1: Characterisation of track geometry*, CEN, Brussels, Belgium, 2008.

[2] ERA, *Trans-European Conventional Rail System Subsystem Infrastructure, Final Draft TSI*, European Railway Agency, Interoperability Unit, 2008.

[3] E. Andersson, M. Berg, and S. Stichel, *Rail Vehicle Dynamics*, Textbook, Division of Rail Vehicles, Department of Aeronautical and Vehicle Engineering, Royal Institute of Technology (KTH), Stockholm, Sweden, ISBN 978-91-7415-272-2, 2007.

[4] M. Lindahl, *Track geometry for high-speed railways*, Railway Technology, Department of Aeronautical and Vehicle Engineering, Royal Institute of Technology (KTH), Stockholm, Sweden, ISSN 1103-470X, 2001.

[5] CEN, *EN13848-5:2008 Railway applications - Track - Track geometry quality - Part 5: Geometric quality levels*, CEN, Brussels, Belgium, 2008.

[6] CEN, *prEN13848-6:2009.4.1 - Railway applications - Track - Track geometry quality - Part 6: Characterisation of Geometric Quality*, CEN, Brussels, Belgium, 2009.

[7] CEN, *EN14363:2005 Railway applications - Testing for the acceptance of running characteristics of railway vehicles - Testing of running behaviour and stationary tests*, CEN, Brussels, Belgium, 2005.

[8] ERA, *Directive 96/48/EC - Interoperability of the trans-European high speed rail system*, European Railway Agency, Interoperability Unit, 2006.

[9] UIC, *Code 518 - Testing and approval of railway vehicles from the point of view of their dynamic behaviour - Safety - Track fatigue - Ride Quality*, UIC, Paris, France, ISBN 2-7461-0353-2, 2005.

[10] Banverket, *BVF 587.02 Spårlägeskontroll och kvalitetsnormer - Central mätvagn STRIX*, Banverket, Borlänge, Sweden, 1997.

[11] Banedanmark, *Banenorm BN1-38-3 - Sporbeliggenhedskontrol og sporkvalitetsnormer*, Banedanmark, Copenhagen, Denmark, 2008.

[12] M. Wrang, *Förstudie. Järnvägssytem för 250 km/h och 320 km/h - delprojekt samverkan fordon-bana*, MiW Konsult AB, Älta, Sweden, 2008.

[13] J. Kawasaki and K. Youcef-Toumi, *Estimation of rail irregularities*, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2002.

[14] UIC, *Code 519 - Method for determining the equivalent conicity*, UIC, Paris, France, ISBN 2-7461-0844-5, 2004.

[15] J. Öberg, E. Andersson, and J. Gunnarsson, *Track access charging with respect to vehicle characteristics*, Banverket, Borlänge, 2007.

[16] The Mathworks. (2007) Matlab. Computer programme.

[17] J. Wingren, *Långtidsprov Regina250 och planer för 2009*, Bombardier, Västerås, http://gronataget.se/upload/PublikaDokument/L%C3%A5ngtidsprov%202009-05-27%20JW.pdf, 2009, accessed 2009-09-24.

[18] ORE, *Frage C 116 - Wechselwirkun zwischen Fahrzeugen und Gleis - Bericht Nr. 8 - Verfahren zur Beurteilung des Komforts eines Schienenfahrzeuges*, ORE, Utrecht, 1977.

[19] CEN, *prEN12299:2008 - Railway applications - Ride comfort for passengers - Measurement and evaluation*, CEN, Brussles, Belgium, 2008.

[20] Banverket. (2008, July) *STRIX data 080725_0750*. DVD.

[21] Banverket, *STRIX - Banverkets resurs för periodisk tillståndskontroll*, Borlänge, Sweden, 2000.

[22] L. Råde and B. Westergren, *BETA - Mathematics Handbook for Science and Engineering*, 5th ed. Lund, Sweden: Studentlitteratur, 2004.

[23] N. Chaar, *Wheelset Structural Flexibility and Track Flexibility in Vehicle-Track Dynamic Interaction*, KTH, Stockholm, Doctoral Thesis ISSN: 1651-7660, ISBN: 978-91-7178-636-4, 2007.

[24] Banverket, *BVS 524.17 Teknisk specifikation för slipning av räler och spårväxlar, version 4.0*, Banverket, Borlänge, Sweden, 2008.

Appendices

A – Table 2, 3 and 4 from BVF 587.02

Banverket's track quality: peak vertical isolated defects

Tabell 2 Kvalitetsnormer för punktfel, höjdläge

			Avvikelse från grundvärde (mm)													
			Höjdläge					Rälsförhöjning								
Kvalitets-klass	sth loktåg km/tim	sth snabbtåg km/tim	Kortvågiga fel 1-25 m våglängd			Långv fel (rikt-värden)		Avvikelse			Skevning mätbas 6 m			Skevning mätbas 3 m		
			A	B	C	A	B	A	B	C	A	B	C	A	B	C
K0	145 -	185 -	2	6	9	7	15	2	4	6	4	9	13	3	6	9
K1	125 - 140	160 - 180	2	6	10	7	15	2	4	7	4	10	15	3	7	10
K2	105 - 120	135 - 155	2	7	12	7	15	2	5	8	4	11	17	3	8	11
K3	75 - 100	95 - 130	4	10	16	-	-	3	7	10	6	13	19	4	9	13
K4	40 - 70	60 - 90	5	13	21	-	-	4	10	13	8	16	23	5	10	15
K5	- 40		6	17	27	-	-	5	12	16	10	19	27	7	12	15
Linje i diagrammet			2 och 3			4		6			5			-		

Banverket's track quality:

peak lateral and track gauge isolated defects and track gauge change over 10 m

Tabell 3. Kvalitetsnormer för punktfel, sidoläge

			Avvikelse från grundvärde (mm)									
			Sidoläge					Spårvidd				
Kvalitets-klass	sth loktåg km/tim	sth snabbtåg km/tim	Kortvågiga fel 1-25 m våglängd			Långvågiga fel (riktvärden)		Avvikelse från nominellt värde 1435 mm			Ändring inom 10 m spårlängd	
			A	B	C	A	B	A	B	C	B	C
K0	145 -	185 -	2	3	5	5	10	±2	±5	+15,-5	7	10
K1	125 - 140	160 - 180	2	4	6	5	10	±2	+7,-5	+20,-5	8	12
K2	105 - 120	135 - 155	2	5	7	5	10	±2	+10,-5	+25,-5	9	15
K3	75 - 100	95 - 130	3	6	10	-	-	±3	+15,-5	+30,-5	10	18
K4	40 - 70	60 - 90	3	10	13	-	-	±4	+20,-5	+35,-5	12	21
K5	- 40		4	13	16	-	-	±5	+20,-5	+35,-5	15	25
Linje i diagrammet			8 och 9			10		11				

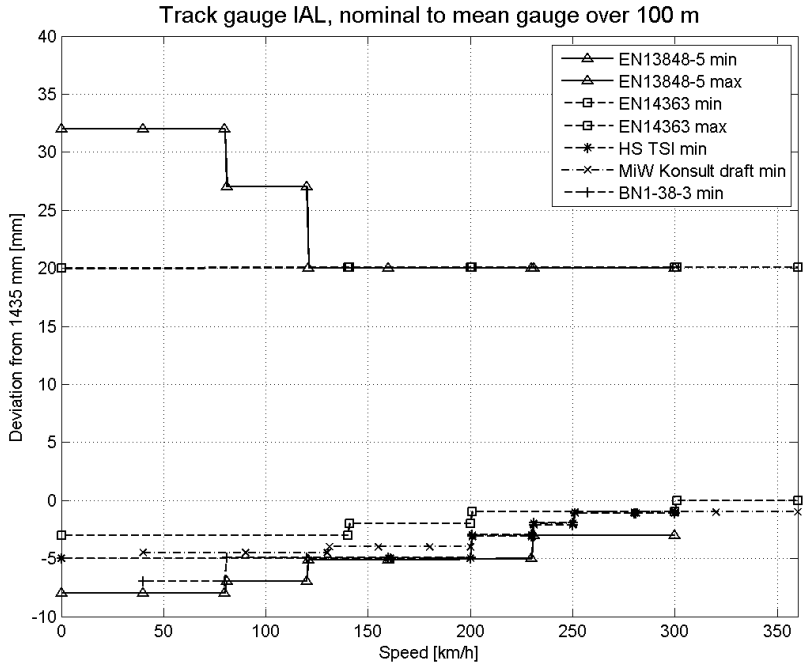
Banverket's track quality: standard deviation

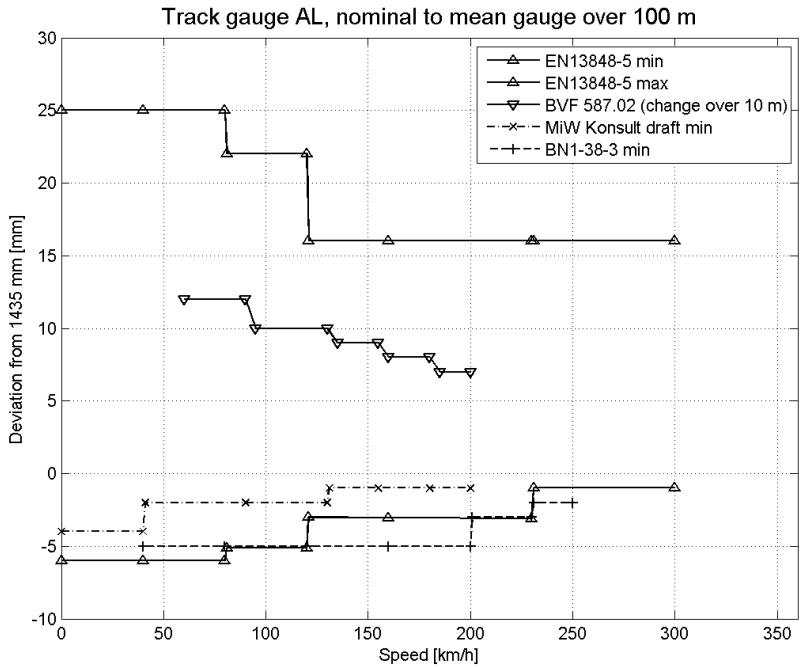
Tabell 4. Komfortgränser för standardavvikelser

Kvalitets-klass	sth loktåg km/tim	sth snabb-tåg km/tim	Komfortgräns			
			Höjdläge σ_H	Rälsförh σ_R	Sidoläge σ_P	Samver-kan σ_S
			mm	mm	mm	mm
K0	145	185	1,1	0,9	1,1	1,6
K1	125-140	160-180	1,3	1,0	1,2	1,7
K2	105-120	135-155	1,5	1,2	1,3	1,9
K3	75 100	95 130	1,9	1,4	1,7	2,4
K4	40- 70	60- 90	2,4	1,8	2,0	3,1
K5	- 40		2.9	2,2	2,4	3,6

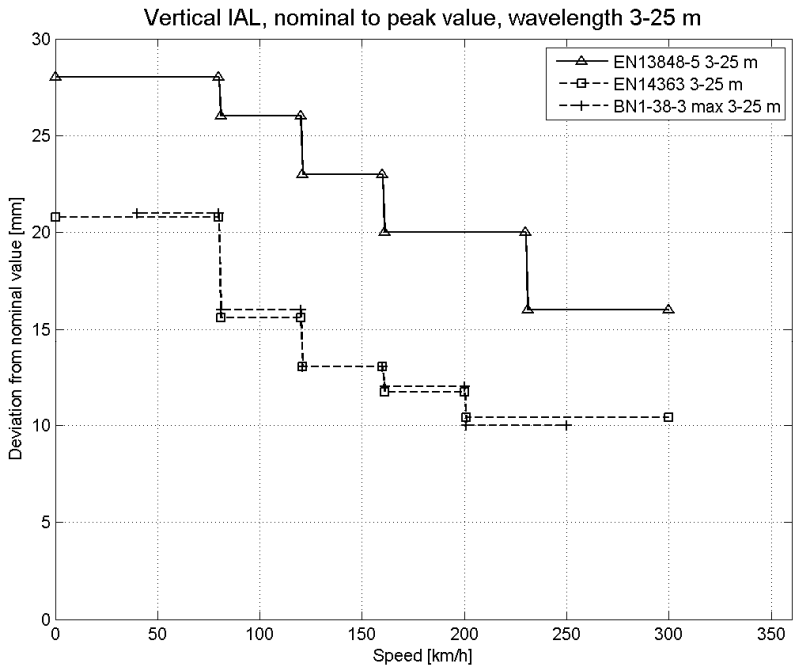
B – Diagrams for comparisons of standards

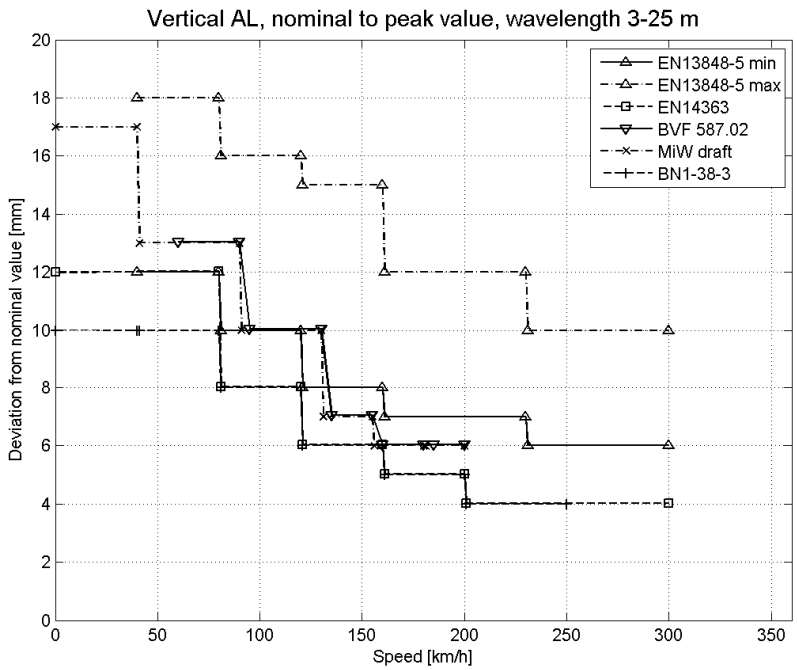
Track gauge irregularities

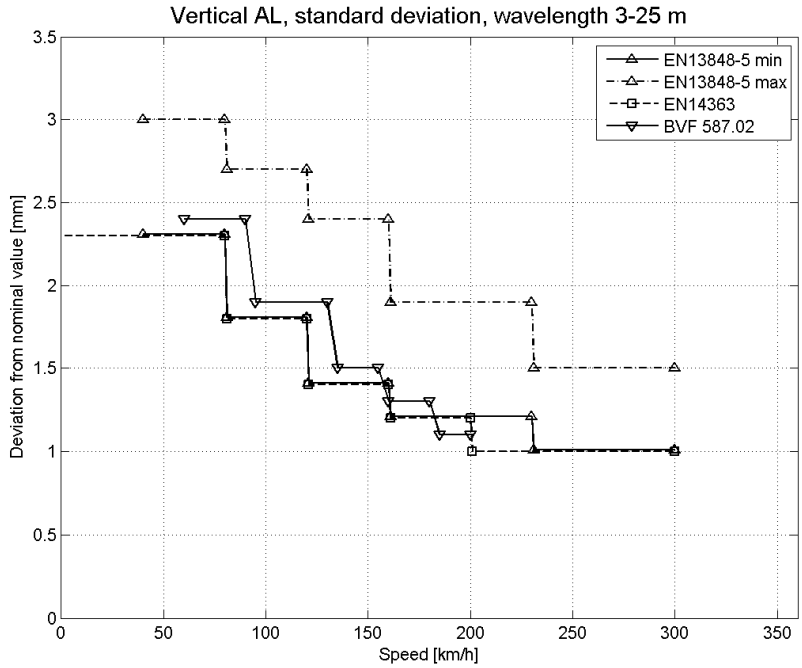




Vertical irregularities

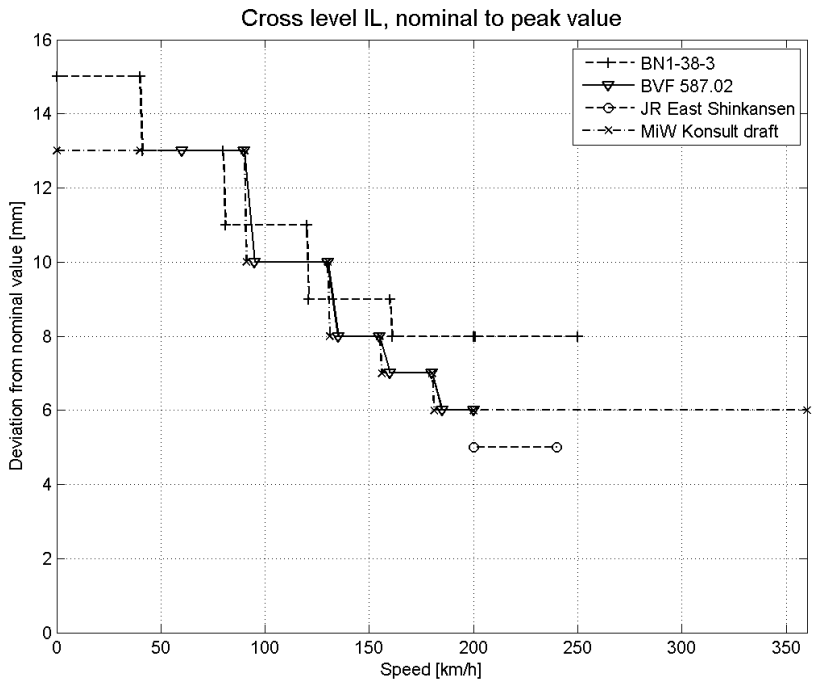


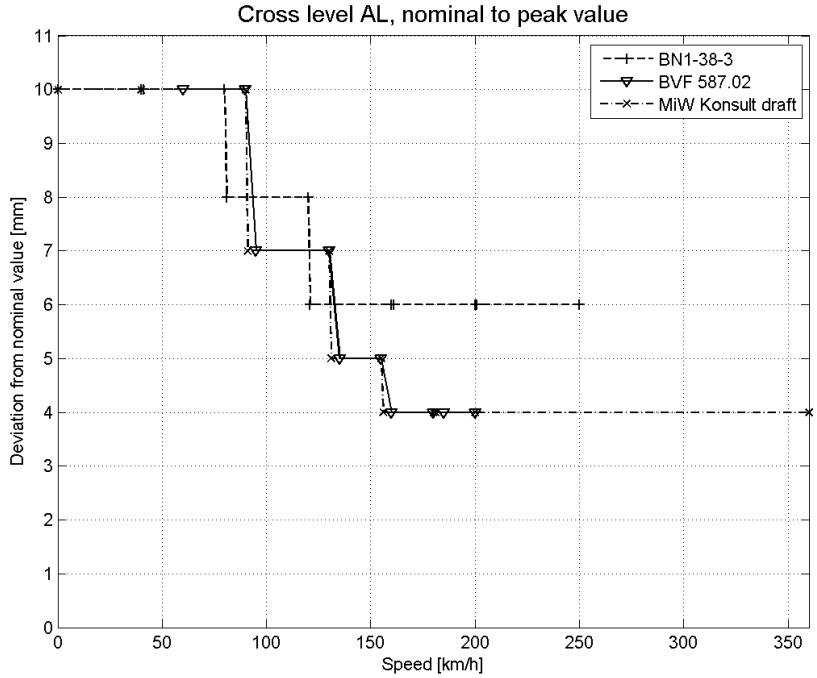




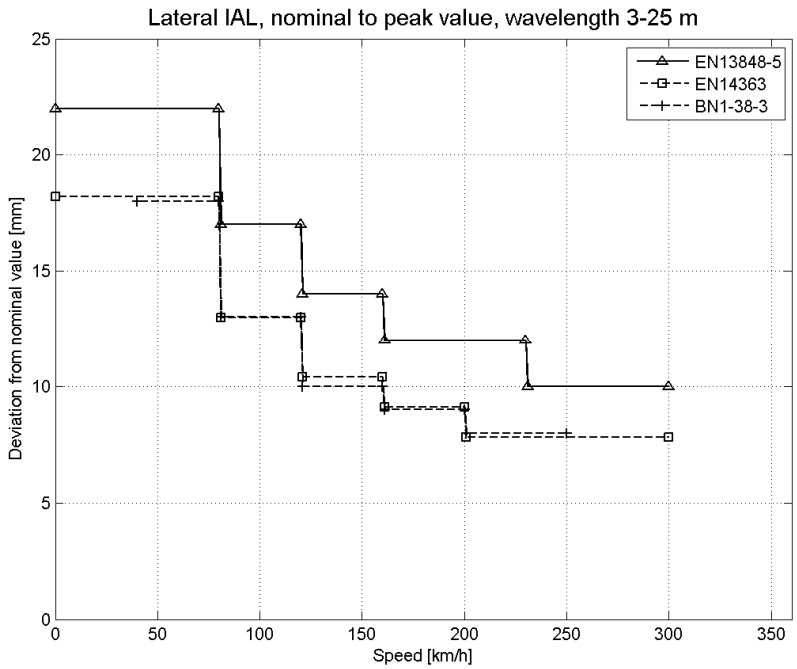
Cross level

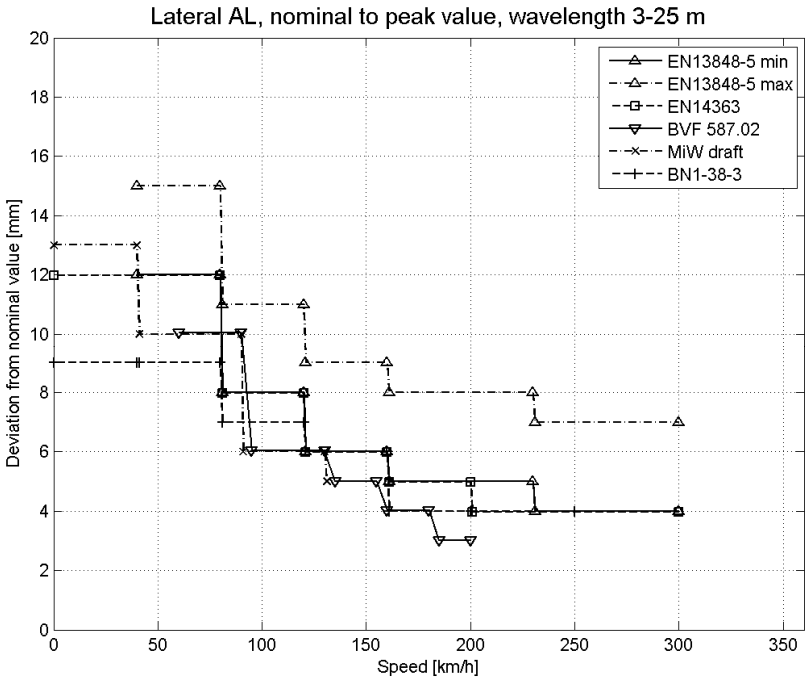
Since there are no IAL limits for cross level errors, the IL limits are shown instead

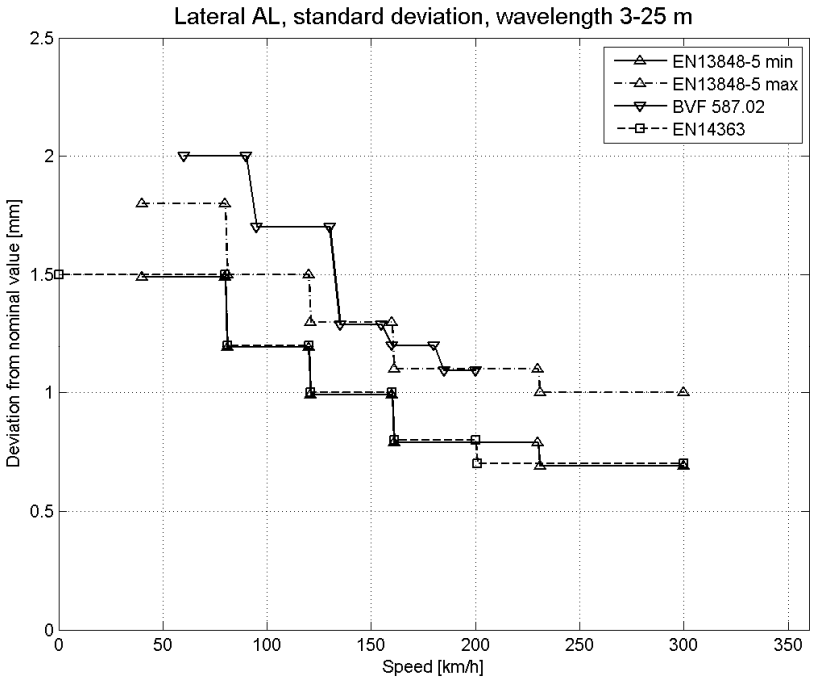




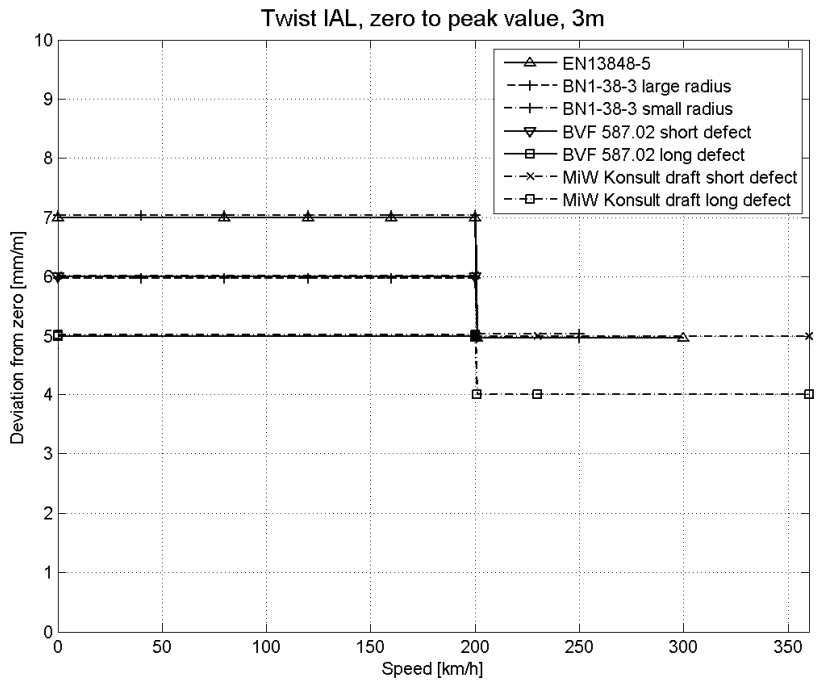
Lateral irregularities

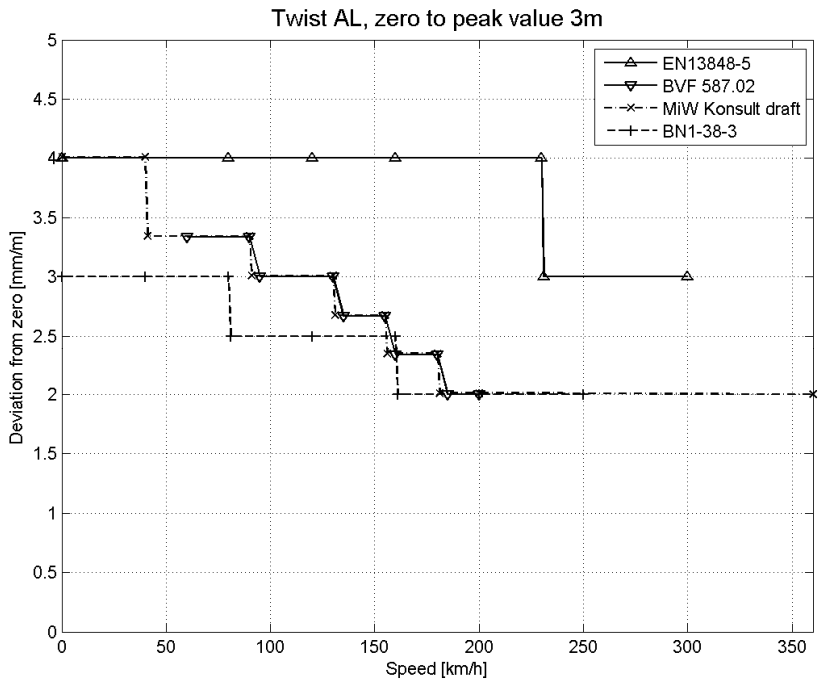



Lateral AL, nominal to peak value, wavelength 3-25 m
EN13848-5 min
EN13848-5 max
EN14363
BVF 587.02
MiW draft
BN1-38-3
Deviation from nominal value [mm]
Speed [km/h]
0
2
4
6
8
10
12
14
16
18
20
0
50
100
150
200
250
300
350


Lateral AL, standard deviation, wavelength 3-25 m
EN13848-5 min
EN13848-5 max
BVF 587.02
EN14363
Deviation from nominal value [mm]
Speed [km/h]
0
0.5
1
1.5
2
2.5
0
50
100
150
200
250
300
350

Twist


Twist IAL, zero to peak value, 3m
EN13848-5
BN1-38-3 large radius
BN1-38-3 small radius
BVF 587.02 short defect
BVF 587.02 long defect
MiW Konsult draft short defect
MiW Konsult draft long defect
Deviation from zero [mm/m]
Speed [km/h]
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
200
250
300
350


Twist AL, zero to peak value 3m
EN13848-5
BVF 587.02
MiW Konsult draft
BN1-38-3
Deviation from zero [mm/m]
Speed [km/h]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
50
100
150
200
250
300
350

C – Results – overview – *Q* forces 20 Hz LP filter

Force	Track	Mean speed [km/h]	Filter [Hz]	Wavelength range [m]	Correlation
Q11	Straight U	276	20	1-25	0.57
Q11	Straight U	276	20	25-70	0.41
Q11	Straight U		20	1-3	-
Q11	**Straight U**	**276**	**20**	**3-10**	**0.77**
Q11	Straight U	276	20	10-25	0.61
Q11	Straight U	292	20	1-25	0.6
Q11	Straight U	292	20	25-70	0.47
Q11	Straight U		20	1-3	-
Q11	**Straight U**	**292**	**20**	**3-10**	**0.71**
Q11	Straight U	292	20	10-25	0.67
Q11	Straight D	275	20	1-25	0.86
Q11	Straight D	275	20	25-70	0.16
Q11	Straight D		20	1-3	-
Q11	**Straight D**	**275**	**20**	**3-10**	**0.92**
Q11	Straight D	275	20	10-25	0.71
Q11	Straight D	288	20	1-25	0.8
Q11	Straight D	288	20	25-70	0.37
Q11	Straight D		20	1-3	-
Q11	**Straight D**	**288**	**20**	**3-10**	**0.91**
Q11	Straight D	288	20	10-25	0.55
Q12	Straight U	276	20	1-25	0.57
Q12	Straight U	276	20	25-70	0.42
Q12	Straight U	-	-	1-3	-
Q12	**Straight U**	**276**	**20**	**3-10**	**0.6**
Q12	Straight U	276	20	10-25	0.57
Q12	**Straight U**	**292**	**20**	**1-25**	**0.71**
Q12	Straight U	292	20	25-70	0.62
Q12	Straight U	-	-	1-3	-
Q12	**Straight U**	**292**	**20**	**3-10**	**0.71**
Q12	Straight U	292	20	10-25	0.7
Q12	**Straight D**	**275**	**20**	**1-25**	**0.66**
Q12	Straight D	275	20	25-70	0.22
Q12	Straight D	-	-	1-3	-
Q12	**Straight D**	**275**	**20**	**3-10**	**0.66**
Q12	Straight D	275	20	10-25	0.58
Q12	**Straight D**	**288**	**20**	**1-25**	**0.8**
Q12	Straight D	288	20	25-70	0.12
Q12	Straight D	-	-	1-3	-
Q12	Straight D	288	20	3-10	0.74
Q12	Straight D	288	20	10-25	0.59

Force	Curve radius [m]	Acceleration [m/s²]	Filter [Hz]	Wavelength range [m]	Correlation
Q1X outer	900 < R < 1500	1.05-1.29	20	1-25	0.61
Q1X outer	**900 < R < 1500**	**1.05-1.29**	**20**	**25-70**	**0.73**
Q1X outer	900 < R < 1500	-	-	1-3	-
Q1X outer	900 < R < 1500	1.05-1.29	20	3-10	0.51
Q1X outer	900 < R < 1500	1.05-1.29	20	10-25	0.57
Q1X outer	**R > 2000**	**1.18-1.30**	**20**	**1-25**	**0.39**
Q1X outer	R > 2000	1.18-1.30	20	25-70	0.33
Q1X outer	R > 2000	-	-	1-3	-
Q1X outer	R > 2000	1.18-1.30	20	3-10	0.04
Q1X outer	R > 2000	1.18-1.30	20	10-25	0.31

D – Results – overview – *Q* forces 140 Hz LP filter

Force	Track	Mean speed [km/h]	Filter [Hz]	Wavelength range [m]	Correlation
Q11	Straight U	275	140	1-25	0.06
Q11	Straight U	275	140	25-70	0.04
Q11	**Straight U**	**275**	**140**	**1-3**	**0.44**
Q11	Straight U	275	140	3-10	0.05
Q11	Straight U	275	140	10-25	0.17
Q11	Straight D	274	140	1-25	0.81
Q11	Straight D	274	140	25-70	0.19
Q11	Straight D	274	140	1-3	0.8
Q11	**Straight D**	**274**	**140**	**3-10**	**0.9**
Q11	Straight D	274	140	10-25	0.76
Q12	Straight U	275	140	1-25	0
Q12	Straight U	275	140	25-70	-0.08
Q12	**Straight U**	**275**	**140**	**1-3**	**0.52**
Q12	Straight U	275	140	3-10	-0.06
Q12	Straight U	275	140	10-25	-0.11
Q12	Straight D	274	140	1-25	0.8
Q12	Straight D	274	140	25-70	0.28
Q12	**Straight D**	**274**	**140**	**1-3**	**0.86**
Q12	Straight D	274	140	3-10	0.83
Q12	Straight D	274	140	10-25	0.77
Force	**Curve radius [m]**	**Acceleration [m/s²]**	**Filter [Hz]**	**Wavelength range [m]**	**Correlation**
Q1X outer	900 < R < 1500	1.00-1.30	140	1-25	0.27
Q1X outer	900 < R < 1500	1.00-1.30	140	25-70	0.27
Q1X outer	**900 < R < 1500**	**1.00-1.30**	**140**	**1-3**	**0.49**
Q1X outer	900 < R < 1500	1.00-1.30	140	3-10	0.25
Q1X outer	900 < R < 1500	1.00-1.30	140	10-25	0.22
Q1X outer	R > 2000	1.05-1.30	140	1-25	0.13
Q1X outer	**R > 2000**	**1.05-1.30**	**140**	**25-70**	**0.27**
Q1X outer	R > 2000	1.05-1.30	140	1-3	-0.05
Q1X outer	R > 2000	1.05-1.30	140	3-10	0.01
Q1X outer	R > 2000	1.05-1.30	140	10-25	-0.03

E – Results – overview – *S* forces 20 Hz LP filter

Force	Track	Mean speed [km/h]	Filter [Hz]	Wavelength range [m]	Correlation
S2 2m	Straight U	276	20	1-25	0.28
S2 2m	**Straight U**	**276**	**20**	**25-70**	**0.41**
S2 2m	Straight U		20	1-3	-
S2 2m	Straight U	276	20	3-10	-0.05
S2 2m	Straight U	276	20	10-25	0.2
S2 2m	Straight U	292	20	1-25	0.33
S2 2m	Straight U	292	20	25-70	-0.02
S2 2m	Straight U		20	1-3	-
S2 2m	Straight U	292	20	3-10	0.1
S2 2m	**Straight U**	**292**	**20**	**10-25**	**0.35**
S2 2m	Straight D	275	20	1-25	0.5
S2 2m	**Straight D**	**275**	**20**	**25-70**	**0.52**
S2 2m	Straight D		20	1-3	-
S2 2m	Straight D	275	20	3-10	0.4
S2 2m	Straight D	275	20	10-25	0.32
S2 2m	Straight D	288	20	1-25	0.45
S2 2m	Straight D	288	20	25-70	0.43
S2 2m	Straight D		20	1-3	-
S2 2m	Straight D	288	20	3-10	0.49
S2 2m	**Straight D**	**288**	**20**	**10-25**	**0.63**
Force	**Curve radius [m]**	**Acceleration range [m/s²]**	**Filter [Hz]**	**Wavelength range [m]**	**Correlation**
S2 2m	900 < R < 1500	1.05-1.29	20	1-25	-0.06
S2 2m	900 < R < 1500	1.05-1.29	20	25-70	0.1
S2 2m	900 < R < 1500			1-3	-
S2 2m	900 < R < 1500	1.05-1.29	20	3-10	0.16
S2 2m	**900 < R < 1500**	**1.05-1.29**	**20**	**10-25**	**0.21**
S2 2m	R > 2000	1.18-1.30	20	1-25	-0.22
S2 2m	**R > 2000**	**1.18-1.30**	**20**	**25-70**	**0.38**
S2 2m	R > 2000			1-3	-
S2 2m	**R > 2000**	**1.18-1.30**	**20**	**3-10**	**-0.38**
S2 2m	R > 2000	1.18-1.30	20	10-25	0.06
Force	**Track**	**Mean speed [km/h]**	**Filter [Hz]**	**-**	**Correlation**
S2 100m	Straight	275			-0.62
S2 100m	Straight	290			-0.79

F – Results – overview – comfort on straight Up-track

Comfort value	Track	Speed [km/h]	Wavelength range [m]	Correlation
Wz vertical / vertical	Straight U	270-300	1-25	0,62
Wz vertical / vertical	Straight U	270-300	25-140	0.77
Wz vertical / vertical	Straight U	270-300	1-3	0.44
Wz vertical / vertical	Straight U	270-300	3-10	0.48
Wz vertical / vertical	Straight U	270-300	10-25	0.63
Wz vertical / vertical	**Straight U**	**270-300**	**25-70**	**0.84**
Wz vertical / vertical	Straight U	270-300	70-140	0.78
ISO vertical / vertical	Straight U	270-300	1-25	0,71
ISO vertical / vertical	Straight U	270-300	25-140	0.53
ISO vertical / vertical	Straight U	270-300	1-3	0.34
ISO vertical / vertical	Straight U	270-300	3-10	0.58
ISO vertical / vertical	Straight U	270-300	10-25	0.72
ISO vertical / vertical	**Straight U**	**270-300**	**25-70**	**0.83**
ISO vertical / vertical	Straight U	270-300	70-140	0.54
Wz lateral / lateral	Straight U	270-300	1-25	-0,26
Wz lateral / lateral	Straight U	270-300	25-140	0.28
Wz lateral / lateral	Straight U	270-300	1-3	-0.32
Wz lateral / lateral	**Straight U**	**270-300**	**3-10**	**-0.50**
Wz lateral / lateral	Straight U	270-300	10-25	-0.16
Wz lateral / lateral	Straight U	270-300	25-70	-0.18
Wz lateral / lateral	Straight U	270-300	70-140	0.35
ISO lateral / lateral	Straight U	270-300	1-25	-0,06
ISO lateral / lateral	**Straight U**	**270-300**	**25-140**	**0.84**
ISO lateral / lateral	Straight U	270-300	1-3	-0.47
ISO lateral / lateral	Straight U	270-300	3-10	-0.48
ISO lateral / lateral	Straight U	270-300	10-25	0.09
ISO lateral / lateral	Straight U	270-300	25-70	0.38
ISO lateral / lateral	Straight U	270-300	70-140	0.77
Wz lateral / combination	Straight U	270-300	1-25	-0,18
Wz lateral / combination	Straight U	270-300	25-140	0.29
Wz lateral / combination	Straight U	270-300	1-3	0.31
Wz lateral / combination	Straight U	270-300	3-10	-0.22
Wz lateral / combination	Straight U	270-300	10-25	-0.09
Wz lateral / combination	Straight U	270-300	25-70	-0.18
Wz lateral / combination	**Straight U**	**270-300**	**70-140**	**0.35**

ISO lateral / combination	Straight U	270-300	1-25	0,11
ISO lateral / combination	**Straight U**	**270-300**	**25-140**	**0.84**
ISO lateral / combination	Straight U	270-300	1-3	0.69
ISO lateral / combination	Straight U	270-300	3-10	0.08
ISO lateral / combination	Straight U	270-300	10-25	0.24
ISO lateral / combination	Straight U	270-300	25-70	0.40
ISO lateral / combination	Straight U	270-300	70-140	0.77
Wz vertical / combination	Straight U	270-300	1-25	0,24
Wz vertical / combination	Straight U	270-300	25-140	0.06
Wz vertical / combination	Straight U	270-300	1-3	0.09
Wz vertical / combination	Straight U	270-300	3-10	-0.07
Wz vertical / combination	Straight U	270-300	10-25	0.24
Wz vertical / combination	**Straight U**	**270-300**	**25-70**	**0.58**
Wz vertical / combination	Straight U	270-300	70-140	-0.00
ISO vertical / combination	Straight U	270-300	1-25	0,4
ISO vertical / combination	Straight U	270-300	25-140	0.18
ISO vertical / combination	Straight U	270-300	1-3	0.16
ISO vertical / combination	Straight U	270-300	3-10	-0.08
ISO vertical / combination	Straight U	270-300	10-25	0.46
ISO vertical / combination	**Straight U**	**270-300**	**25-70**	**0.68**
ISO vertical / combination	Straight U	270-300	70-140	0.08

G – Results – overview – comfort on straight Down-track

Comfort value	Track	Speed [km/h]	Wavelength range [m]	Correlation
Wz vertical / vertical	Straight D	270-300	1-25	0.29
Wz vertical / vertical	Straight D	270-300	25-140	0.72
Wz vertical / vertical	Straight D	270-300	1-3	0.51
Wz vertical / vertical	Straight D	270-300	3-10	0.40
Wz vertical / vertical	Straight D	270-300	10-25	0.20
Wz vertical / vertical	**Straight D**	**270-300**	**25-70**	**0.75**
Wz vertical / vertical	Straight D	270-300	70-140	0.54
ISO vertical / vertical	Straight D	270-300	1-25	0.73
ISO vertical / vertical	Straight D	270-300	25-140	0.29
ISO vertical / vertical	**Straight D**	**270-300**	**1-3**	**0.83**
ISO vertical / vertical	Straight D	270-300	3-10	0.81
ISO vertical / vertical	Straight D	270-300	10-25	0.66
ISO vertical / vertical	Straight D	270-300	25-70	0.24
ISO vertical / vertical	Straight D	270-300	70-140	0.19
Wz lateral / lateral	**Straight D**	**270-300**	**1-25**	**0.84**
Wz lateral / lateral	Straight D	270-300	25-140	0.41
Wz lateral / lateral	**Straight D**	**270-300**	**1-3**	**0.84**
Wz lateral / lateral	Straight D	270-300	3-10	0.79
Wz lateral / lateral	Straight D	270-300	10-25	0.82
Wz lateral / lateral	Straight D	270-300	25-70	0.80
Wz lateral / lateral	Straight D	270-300	70-140	0.36
ISO lateral / lateral	Straight D	270-300	1-25	0.50
ISO lateral / lateral	**Straight D**	**270-300**	**25-140**	**0.74**
ISO lateral / lateral	Straight D	270-300	1-3	0.62
ISO lateral / lateral	Straight D	270-300	3-10	0.59
ISO lateral / lateral	Straight D	270-300	10-25	0.43
ISO lateral / lateral	Straight D	270-300	25-70	0.73
ISO lateral / lateral	Straight D	270-300	70-140	0.72
Wz lateral / combination	**Straight D**	**270-300**	**1-25**	**0.84**
Wz lateral / combination	Straight D	270-300	25-140	0.43
Wz lateral / combination	Straight D	270-300	1-3	0.38
Wz lateral / combination	Straight D	270-300	3-10	0.67
Wz lateral / combination	Straight D	270-300	10-25	0.79
Wz lateral / combination	Straight D	270-300	25-70	0.81
Wz lateral / combination	Straight D	270-300	70-140	0.36

ISO lateral / combination	Straight D	270-300	1-25	0.50
ISO lateral / combination	**Straight D**	**270-300**	**25-140**	**0.75**
ISO lateral / combination	Straight D	270-300	1-3	0.23
ISO lateral / combination	Straight D	270-300	3-10	0.48
ISO lateral / combination	Straight D	270-300	10-25	0.42
ISO lateral / combination	Straight D	270-300	25-70	0.74
ISO lateral / combination	Straight D	270-300	70-140	0.72
Wz vertical / combination	Straight D	270-300	1-25	0.60
Wz vertical / combination	Straight D	270-300	25-140	0.18
Wz vertical / combination	Straight D	270-300	1-3	0.62
Wz vertical / combination	Straight D	270-300	3-10	0.58
Wz vertical / combination	**Straight D**	**270-300**	**10-25**	**0.70**
Wz vertical / combination	Straight D	270-300	25-70	0.54
Wz vertical / combination	Straight D	270-300	70-140	0.12
ISO vertical / combination	**Straight D**	**270-300**	**1-25**	**0.66**
ISO vertical / combination	Straight D	270-300	25-140	0.37
ISO vertical / combination	Straight D	270-300	1-3	0.23
ISO vertical / combination	Straight D	270-300	3-10	0.38
ISO vertical / combination	**Straight D**	**270-300**	**10-25**	**0.66**
ISO vertical / combination	**Straight D**	**270-300**	**25-70**	**0.66**
ISO vertical / combination	Straight D	270-300	70-140	0.28

H – Results – overview – comfort in curves *R* > 2000 m

Comfort value	Curve radius [m]	Speed [km/h]	Wavelength range [m]	Correlation
Wz vertical / vertical	**R > 2000**	**240-270**	**1-25**	**0.86**
Wz vertical / vertical	R > 2000	240-270	25-140	0.78
Wz vertical / vertical	R > 2000	240-270	1-3	0.66
Wz vertical / vertical	R > 2000	240-270	3-10	0.80
Wz vertical / vertical	**R > 2000**	**240-270**	**10-25**	**0.86**
Wz vertical / vertical	**R > 2000**	**240-270**	**25-70**	**0.86**
Wz vertical / vertical	R > 2000	240-270	70-140	0.71
ISO vertical / vertical	**R > 2000**	**240-270**	**1-25**	**0.82**
ISO vertical / vertical	R > 2000	240-270	25-140	0.58
ISO vertical / vertical	R > 2000	240-270	1-3	0.65
ISO vertical / vertical	R > 2000	240-270	3-10	0.78
ISO vertical / vertical	R > 2000	240-270	10-25	0.81
ISO vertical / vertical	R > 2000	240-270	25-70	0.67
ISO vertical / vertical	R > 2000	240-270	70-140	0.52
Wz lateral / lateral	R > 2000	240-270	1-25	0.05
Wz lateral / lateral	**R > 2000**	**240-270**	**25-140**	**0.32**
Wz lateral / lateral	R > 2000	240-270	1-3	0.10
Wz lateral / lateral	R > 2000	240-270	3-10	0.02
Wz lateral / lateral	R > 2000	240-270	10-25	0.06
Wz lateral / lateral	R > 2000	240-270	25-70	0.27
Wz lateral / lateral	R > 2000	240-270	70-140	0.28
ISO lateral / lateral	R > 2000	240-270	1-25	-0.08
ISO lateral / lateral	**R > 2000**	**240-270**	**25-140**	**0.19**
ISO lateral / lateral	R > 2000	240-270	1-3	-0.00
ISO lateral / lateral	R > 2000	240-270	3-10	-0.09
ISO lateral / lateral	R > 2000	240-270	10-25	-0.07
ISO lateral / lateral	R > 2000	240-270	25-70	0.15
ISO lateral / lateral	R > 2000	240-270	70-140	0.17
Wz lateral / combination	R > 2000	240-270	1-25	0.30
Wz lateral / combination	R > 2000	240-270	25-140	0.34
Wz lateral / combination	**R > 2000**	**240-270**	**1-3**	**0.65**
Wz lateral / combination	R > 2000	240-270	3-10	0.40
Wz lateral / combination	R > 2000	240-270	10-25	0.46
Wz lateral / combination	R > 2000	240-270	25-70	0.40
Wz lateral / combination	R > 2000	240-270	70-140	0.29

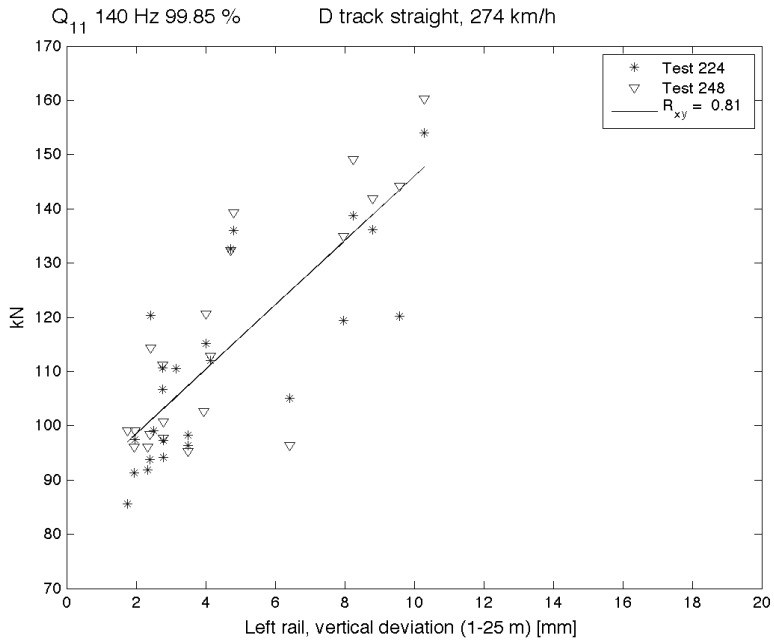
ISO lateral / combination	R > 2000	240-270	1-25	0.15
ISO lateral / combination	R > 2000	240-270	25-140	0.21
ISO lateral / combination	**R > 2000**	**240-270**	**1-3**	**0.53**
ISO lateral / combination	R > 2000	240-270	3-10	0.26
ISO lateral / combination	R > 2000	240-270	10-25	0.30
ISO lateral / combination	R > 2000	240-270	25-70	0.26
ISO lateral / combination	R > 2000	240-270	70-140	0.18
Wz vertical / combination	**R > 2000**	**240-270**	**1-25**	**0.63**
Wz vertical / combination	R > 2000	240-270	25-140	0.39
Wz vertical / combination	R > 2000	240-270	1-3	0.10
Wz vertical / combination	R > 2000	240-270	3-10	0.44
Wz vertical / combination	R > 2000	240-270	10-25	0.52
Wz vertical / combination	R > 2000	240-270	25-70	0.57
Wz vertical / combination	R > 2000	240-270	70-140	0.36
ISO vertical / combination	**R > 2000**	**240-270**	**1-25**	**0.59**
ISO vertical / combination	R > 2000	240-270	25-140	0.35
ISO vertical / combination	R > 2000	240-270	1-3	0.12
ISO vertical / combination	R > 2000	240-270	3-10	0.41
ISO vertical / combination	R > 2000	240-270	10-25	0.49
ISO vertical / combination	R > 2000	240-270	25-70	0.54
ISO vertical / combination	R > 2000	240-270	70-140	0.32

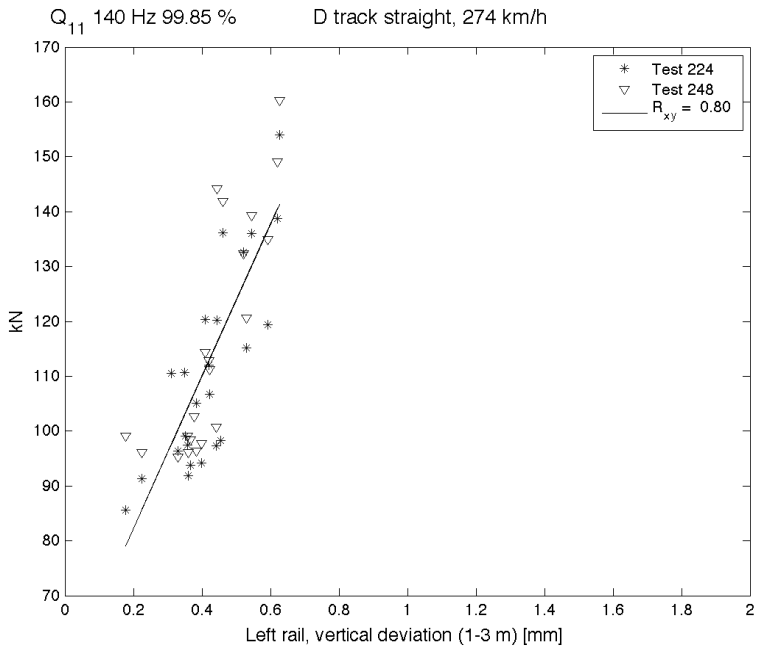
I – Results – overview – comfort in curves 900 m < *R* < 1500 m

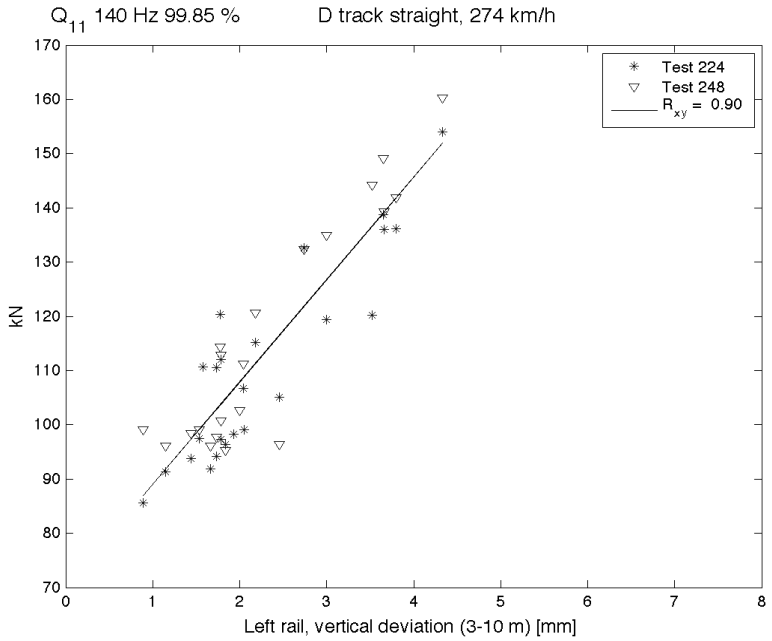
Comfort value	Curve radius [m]	Speed [km/h]	Wavelength range [m]	Correlation
Wz vertical / vertical	**900 < R < 1500**	**150-200**	**1-25**	**0.84**
Wz vertical / vertical	900 < R < 1500	150-200	25-140	0.54
Wz vertical / vertical	900 < R < 1500	150-200	1-3	0.52
Wz vertical / vertical	900 < R < 1500	150-200	3-10	0.79
Wz vertical / vertical	900 < R < 1500	150-200	10-25	0.72
Wz vertical / vertical	900 < R < 1500	150-200	25-70	0.71
Wz vertical / vertical	900 < R < 1500	150-200	70-140	0.48
ISO vertical / vertical	900 < R < 1500	150-200	1-25	0.75
ISO vertical / vertical	900 < R < 1500	150-200	25-140	0.36
ISO vertical / vertical	900 < R < 1500	150-200	1-3	0.83
ISO vertical / vertical	**900 < R < 1500**	**150-200**	**3-10**	**0.90**
ISO vertical / vertical	900 < R < 1500	150-200	10-25	0.50
ISO vertical / vertical	900 < R < 1500	150-200	25-70	0.44
ISO vertical / vertical	900 < R < 1500	150-200	70-140	0.34
Wz lateral / lateral	900 < R < 1500	150-200	1-25	0.46
Wz lateral / lateral	900 < R < 1500	150-200	25-140	0.36
Wz lateral / lateral	900 < R < 1500	150-200	1-3	0.25
Wz lateral / lateral	900 < R < 1500	150-200	3-10	0.29
Wz lateral / lateral	900 < R < 1500	150-200	10-25	0.51
Wz lateral / lateral	**900 < R < 1500**	**150-200**	**25-70**	**0.53**
Wz lateral / lateral	900 < R < 1500	150-200	70-140	0.31
ISO lateral / lateral	900 < R < 1500	150-200	1-25	0.23
ISO lateral / lateral	900 < R < 1500	150-200	25-140	0.47
ISO lateral / lateral	900 < R < 1500	150-200	1-3	-0.05
ISO lateral / lateral	900 < R < 1500	150-200	3-10	-0.00
ISO lateral / lateral	900 < R < 1500	150-200	10-25	0.34
ISO lateral / lateral	**900 < R < 1500**	**150-200**	**25-70**	**0.72**
ISO lateral / lateral	900 < R < 1500	150-200	70-140	0.42
Wz lateral / combination	**900 < R < 1500**	**150-200**	**1-25**	**0.59**
Wz lateral / combination	900 < R < 1500	150-200	25-140	0.38
Wz lateral / combination	900 < R < 1500	150-200	1-3	0.45
Wz lateral / combination	900 < R < 1500	150-200	3-10	0.51
Wz lateral / combination	900 < R < 1500	150-200	10-25	0.55
Wz lateral / combination	900 < R < 1500	150-200	25-70	0.57
Wz lateral / combination	900 < R < 1500	150-200	70-140	0.33

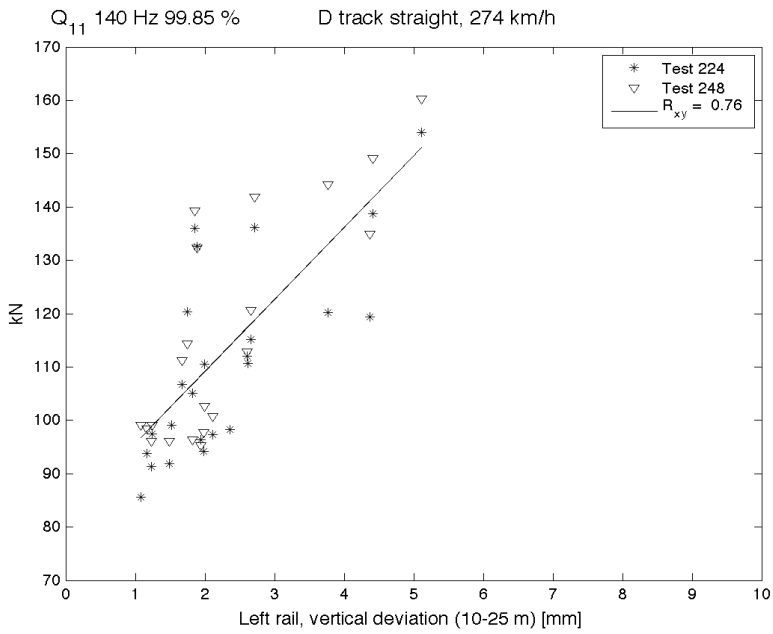
ISO lateral / combination	900 < R < 1500	150-200	1-25	0.41
ISO lateral / combination	**900 < R < 1500**	**150-200**	**25-140**	**0.48**
ISO lateral / combination	900 < R < 1500	150-200	1-3	0.37
ISO lateral / combination	900 < R < 1500	150-200	3-10	0.35
ISO lateral / combination	900 < R < 1500	150-200	10-25	0.33
ISO lateral / combination	900 < R < 1500	150-200	10-25	0.43
ISO lateral / combination	900 < R < 1500	150-200	70-140	0.43
Wz vertical /combination	**900 < R < 1500**	**150-200**	**1-25**	**0.33**
Wz vertical /combination	900 < R < 1500	150-200	25-140	0.21
Wz vertical /combination	900 < R < 1500	150-200	1-3	0.09
Wz vertical /combination	900 < R < 1500	150-200	3-10	0.21
Wz vertical /combination	900 < R < 1500	150-200	10-25	0.21
Wz vertical /combination	900 < R < 1500	150-200	25-70	0.27
Wz vertical /combination	900 < R < 1500	150-200	70-140	0.19
ISO vertical/combination	**900 < R < 1500**	**150-200**	**1-25**	**0.39**
ISO vertical/combination	900 < R < 1500	150-200	25-140	0.10
ISO vertical/combination	900 < R < 1500	150-200	1-3	0.08
ISO vertical/combination	900 < R < 1500	150-200	3-10	0.25
ISO vertical/combination	900 < R < 1500	150-200	10-25	0.21
ISO vertical/combination	900 < R < 1500	150-200	25-70	0.10
ISO vertical/combination	900 < R < 1500	150-200	70-140	0.09

J – Forces vs. track irregularities – Straight Down-track Q_{11} 140 Hz LP filter

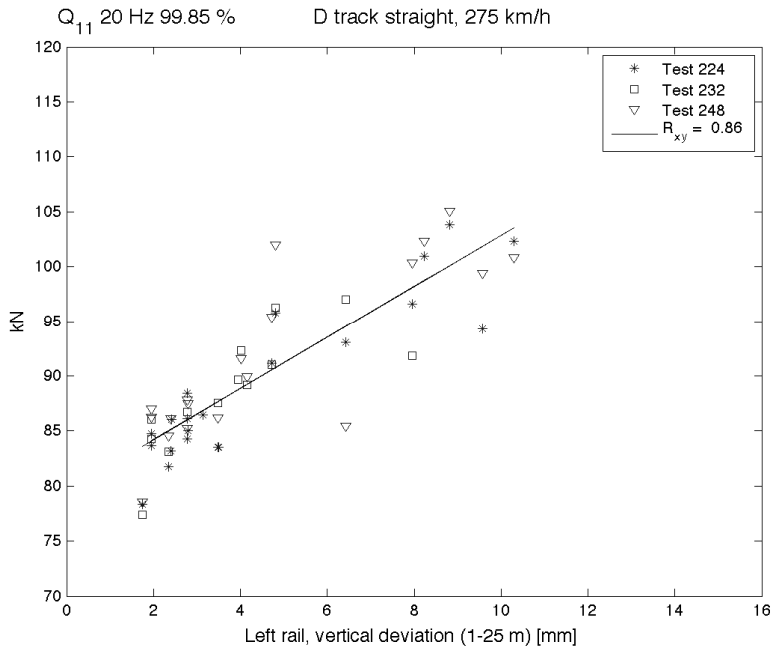


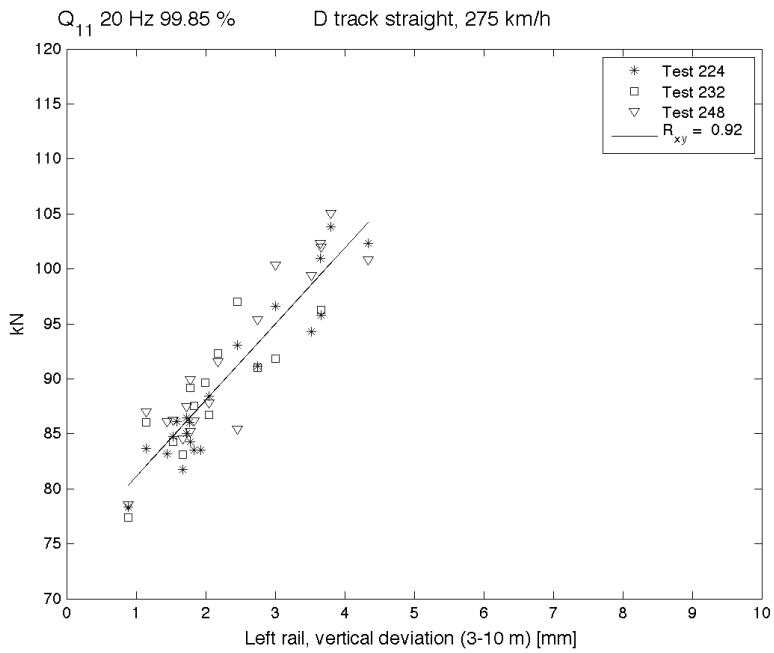


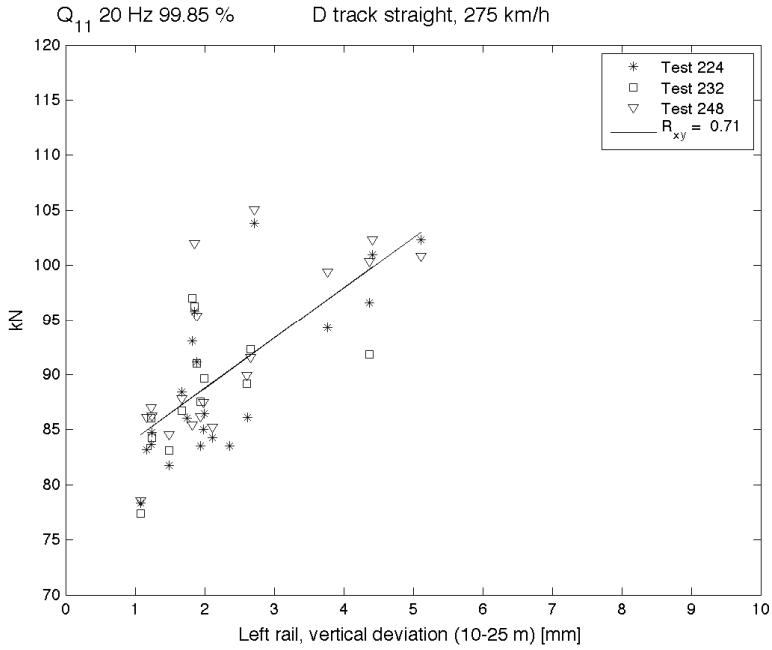

Q11 140 Hz 99.85 %
D track straight, 274 km/h
Test 224
Test 248
Rxy = 0.90
kN
Left rail, vertical deviation (3-10 m) [mm]


Q11 140 Hz 99.85 %
D track straight, 274 km/h
Test 224
Test 248
Rxy = 0.76
kN
Left rail, vertical deviation (10-25 m) [mm]

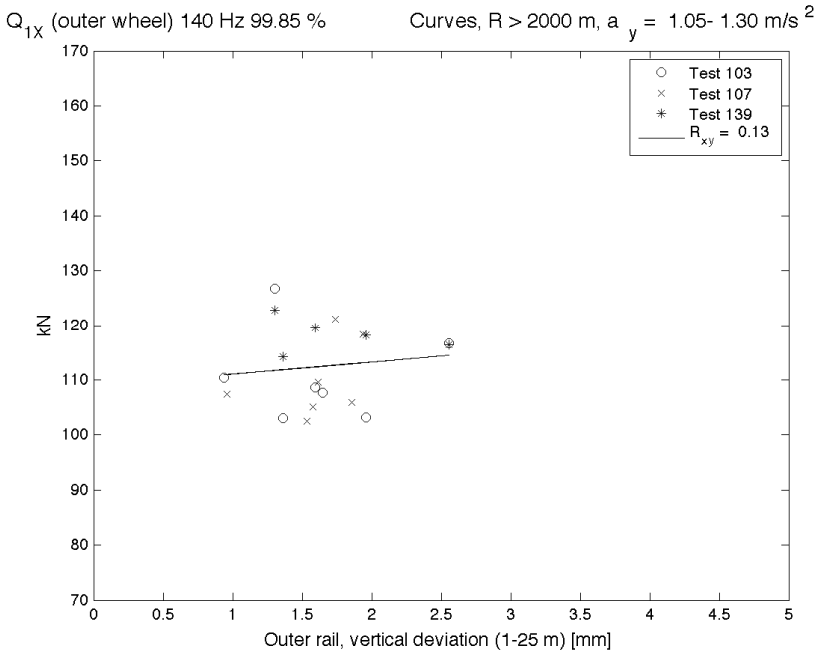
K – Forces vs. track irregularities – Straight Down-track Q_{11} 20 Hz LP filter

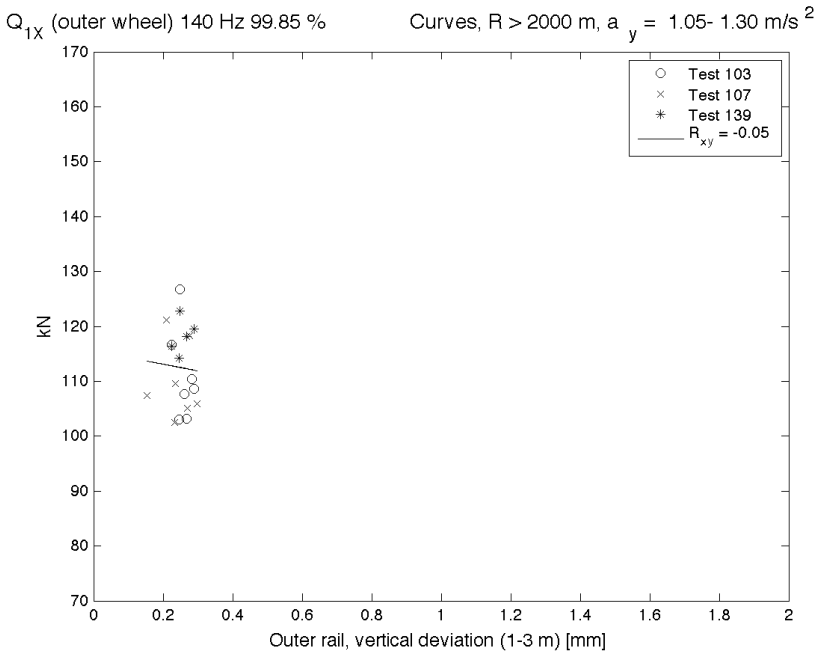


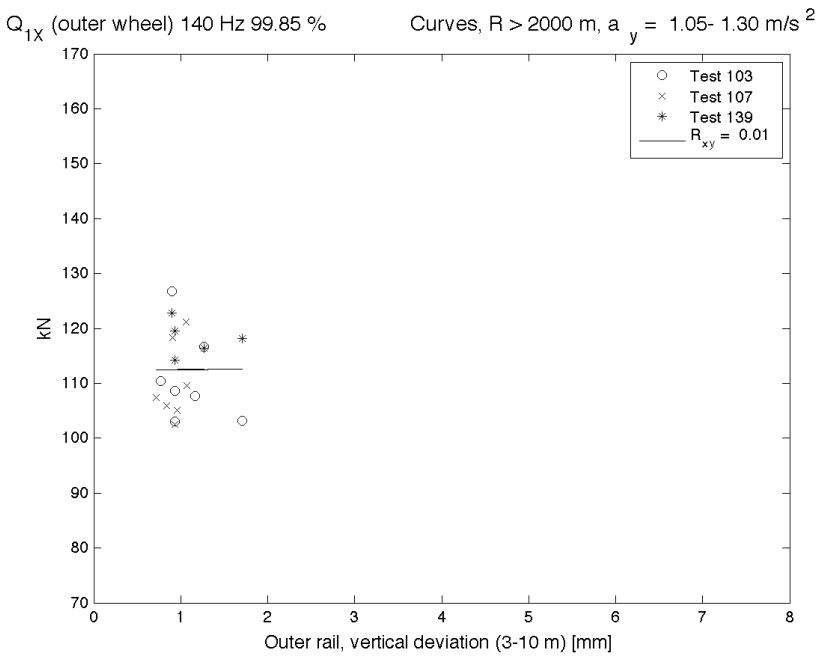


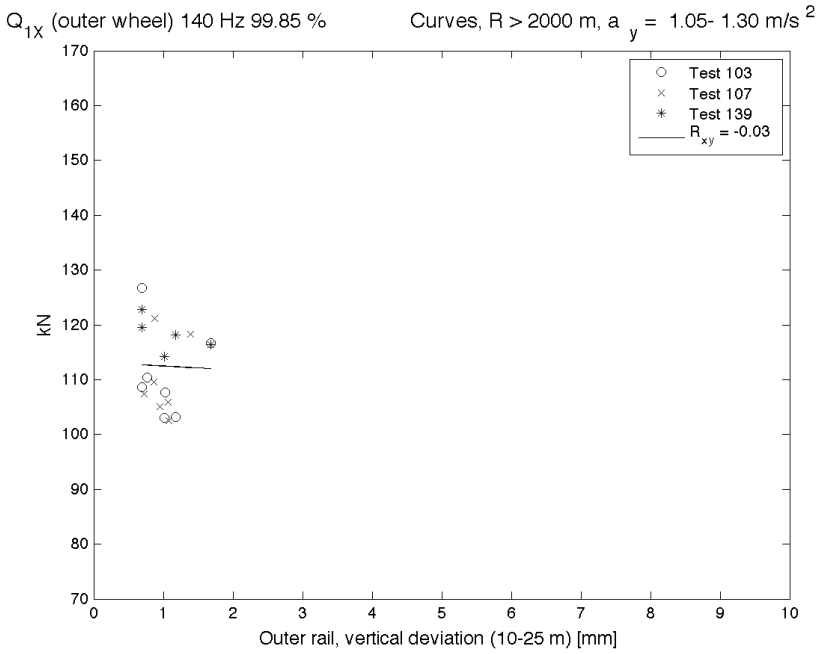

Q11 20 Hz 99.85 %
D track straight, 275 km/h
Test 224
Test 232
Test 248
Rxy = 0.71
kN
Left rail, vertical deviation (10-25 m) [mm]

L – Forces vs. track irregularities – Large radius curves Q_{1X} 140 Hz LP filter

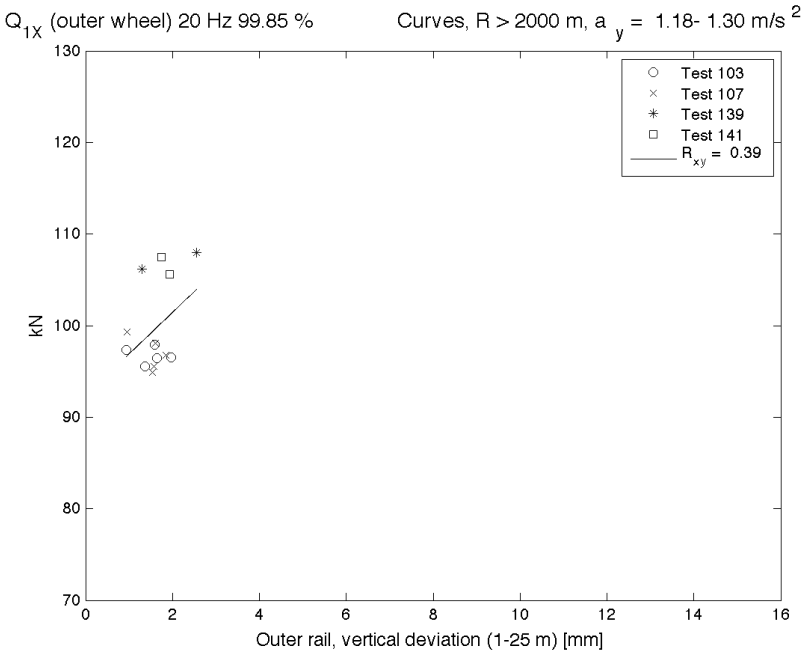


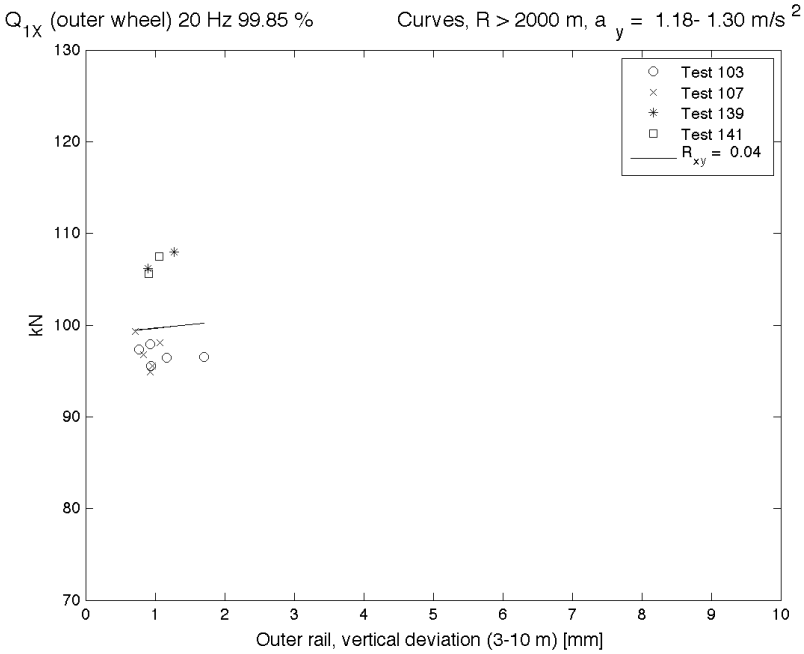


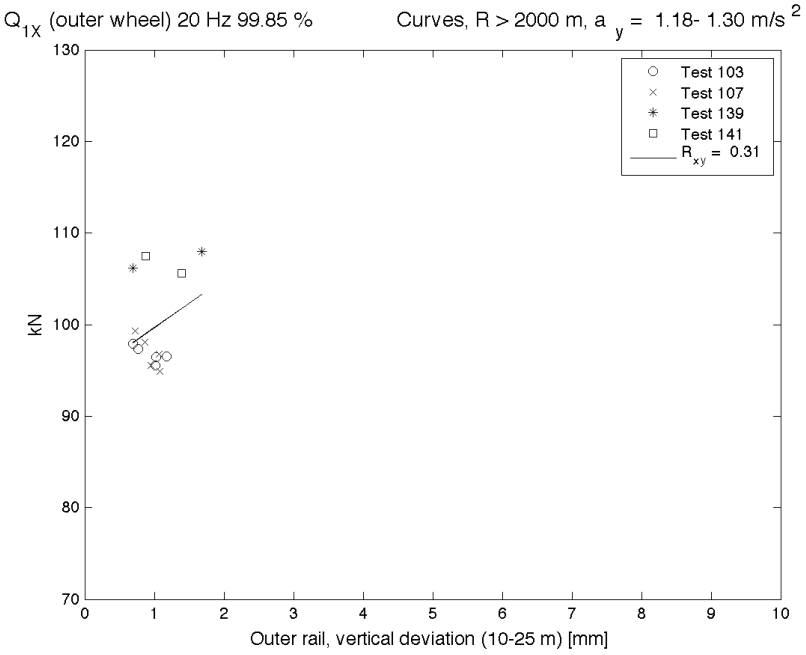

Q1X (outer wheel) 140 Hz 99.85 %
Curves, R > 2000 m, a y = 1.05- 1.30 m/s 2
Test 103
Test 107
Test 139
Rxy = 0.01
kN
Outer rail, vertical deviation (3-10 m) [mm]


Q1X (outer wheel) 140 Hz 99.85 %
Curves, R > 2000 m, a y = 1.05- 1.30 m/s 2
Test 103
Test 107
Test 139
Rxy = -0.03
kN
Outer rail, vertical deviation (10-25 m) [mm]

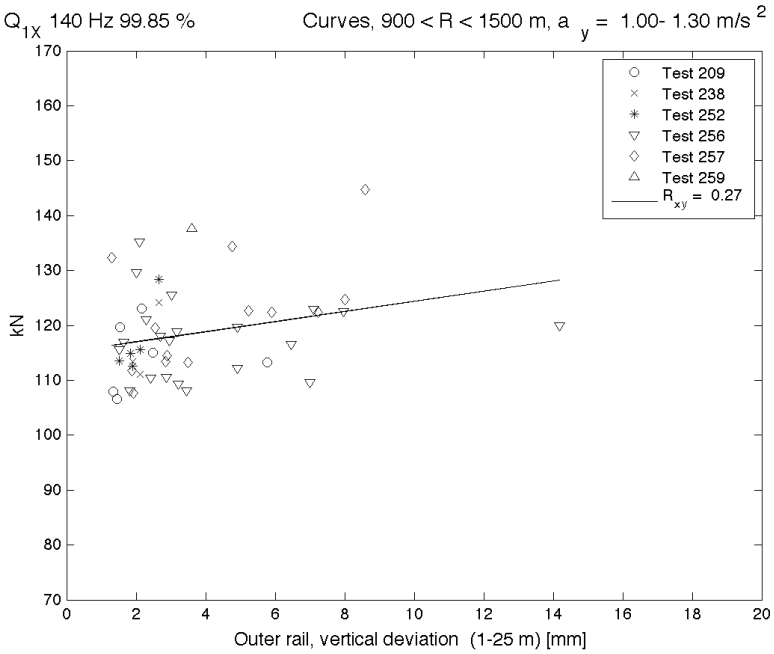
M – Forces vs. track irregularities – Large radius curves Q_{1X} 20 Hz LP filter

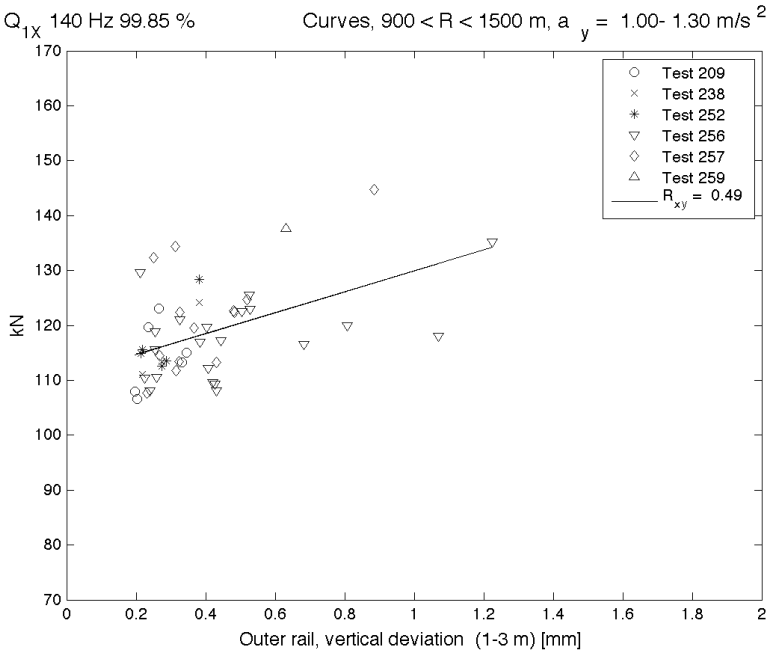


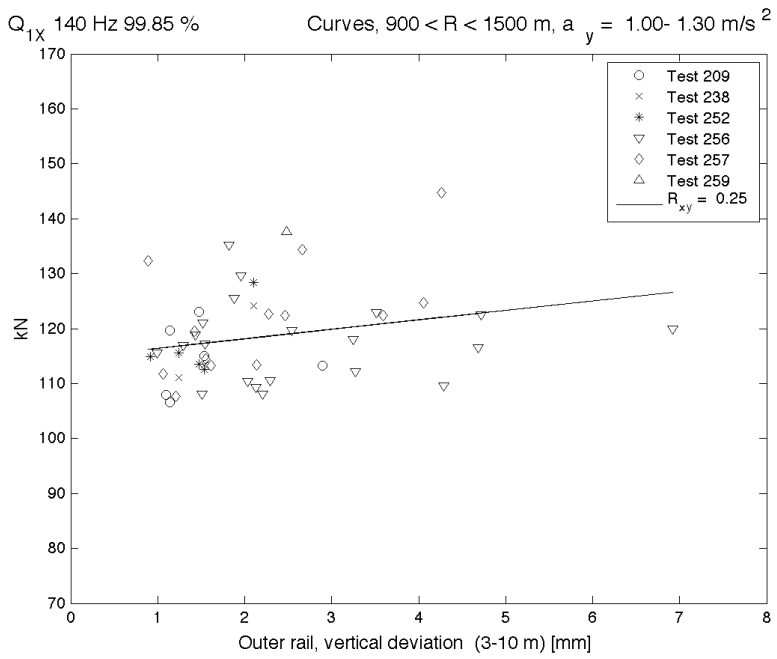


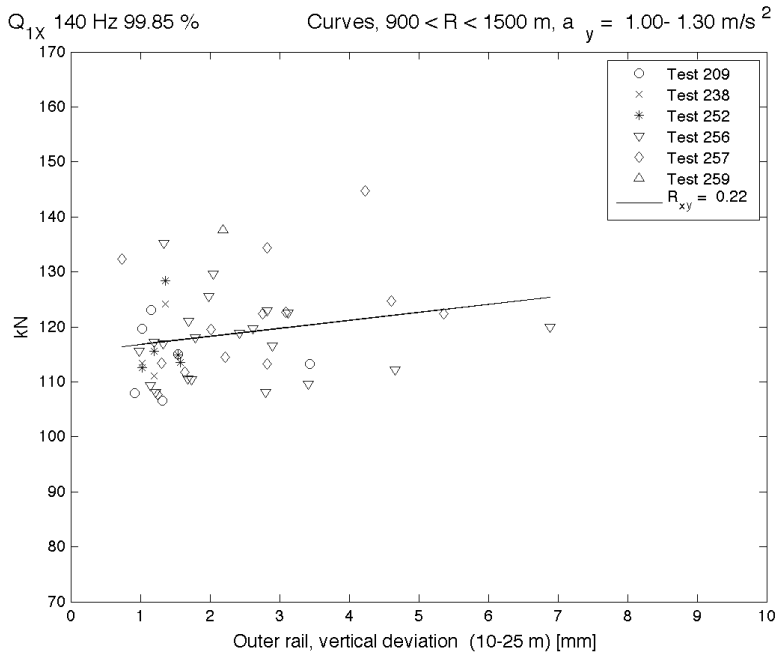

Q1X (outer wheel) 20 Hz 99.85 %
Curves, R > 2000 m, a y = 1.18- 1.30 m/s 2
Test 103
Test 107
Test 139
Test 141
Rxy = 0.31
kN
130
120
110
100
90
80
70
0
1
2
3
4
5
6
7
8
9
10
Outer rail, vertical deviation (10-25 m) [mm]

N – Forces vs. track irregularities – Medium radius curves Q_{1X} 140 Hz LP filter

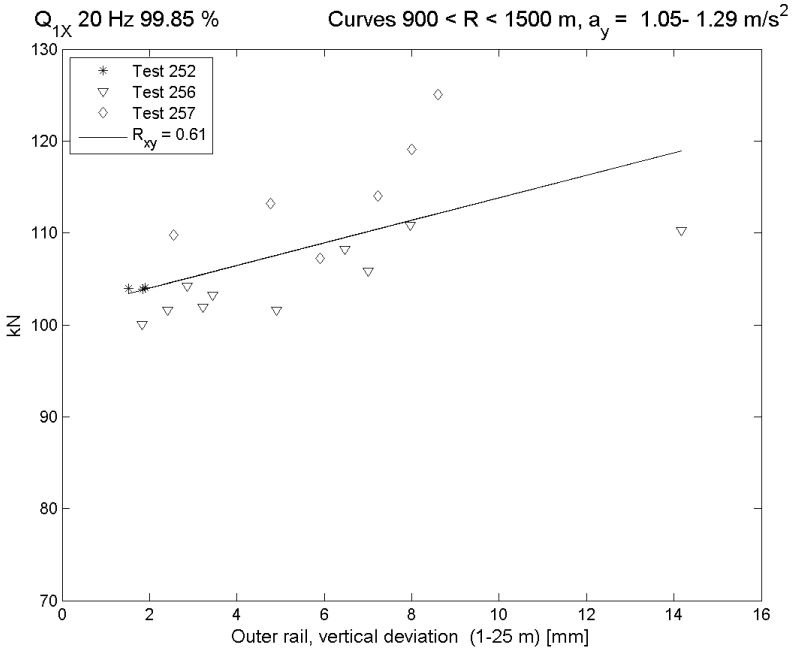


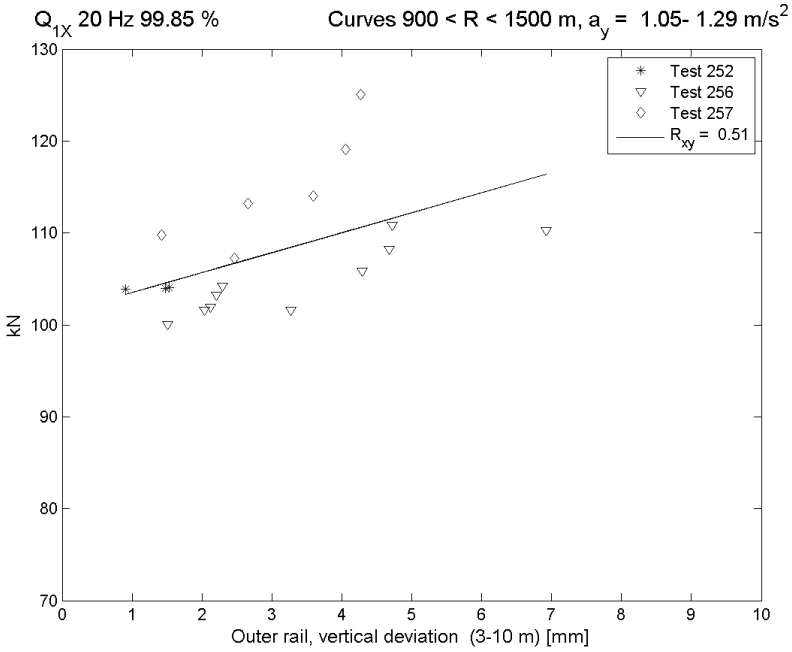


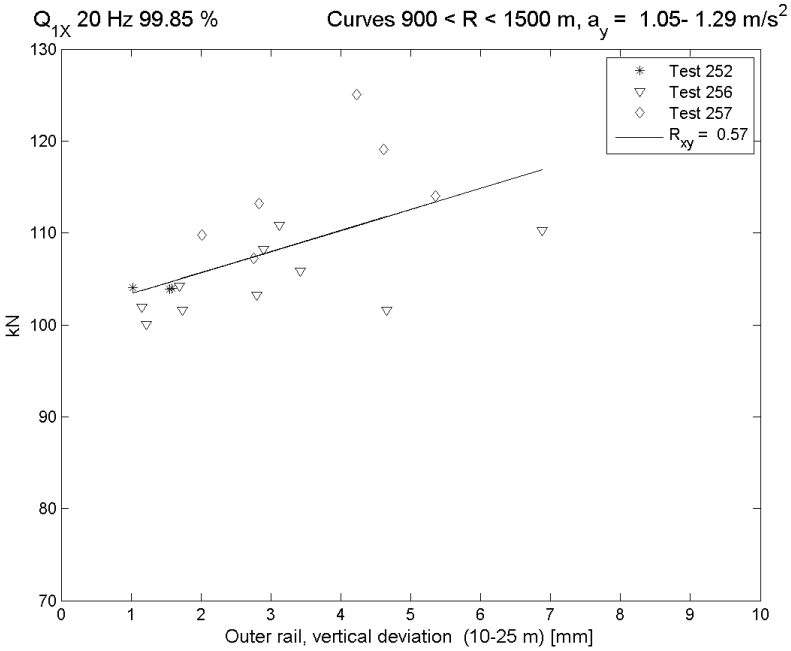

Q1X 140 Hz 99.85 %
Curves, 900 < R < 1500 m, a y = 1.00- 1.30 m/s 2
Test 209
Test 238
Test 252
Test 256
Test 257
Test 259
Rxy = 0.25
kN
Outer rail, vertical deviation (3-10 m) [mm]

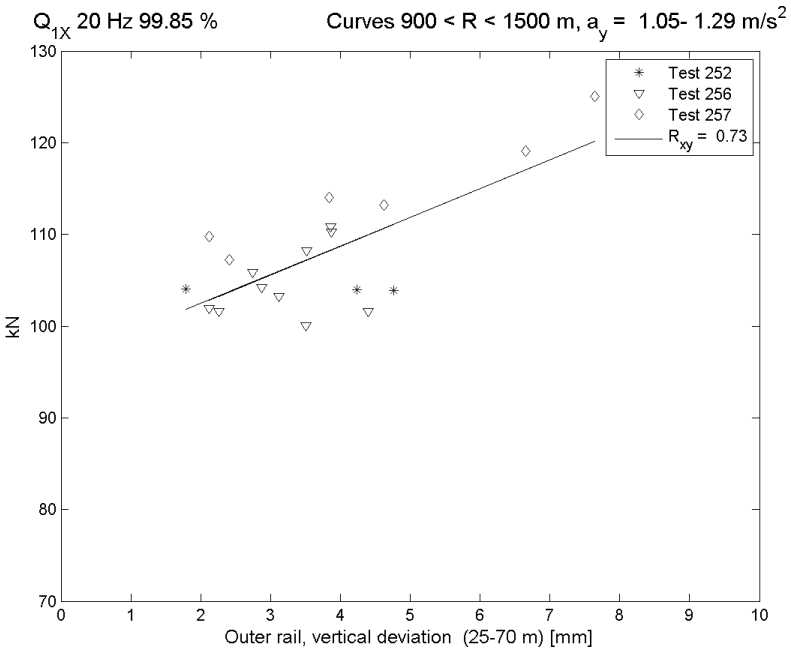

Q1X 140 Hz 99.85 %
Curves, 900 < R < 1500 m, a y = 1.00- 1.30 m/s 2
Test 209
Test 238
Test 252
Test 256
Test 257
Test 259
Rxy = 0.22
kN
Outer rail, vertical deviation (10-25 m) [mm]

O – Forces vs. track irregularities – Medium radius curves Q_{1X} 20 Hz LP filter

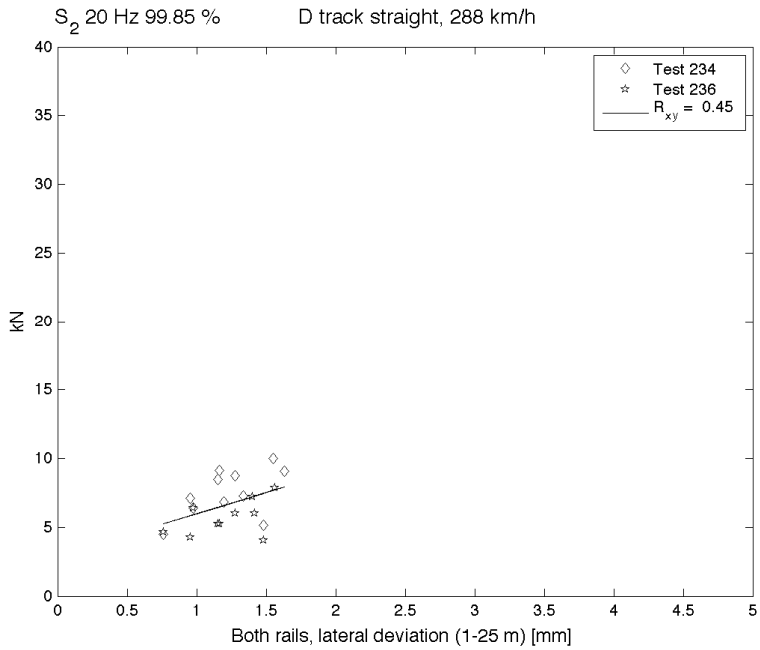


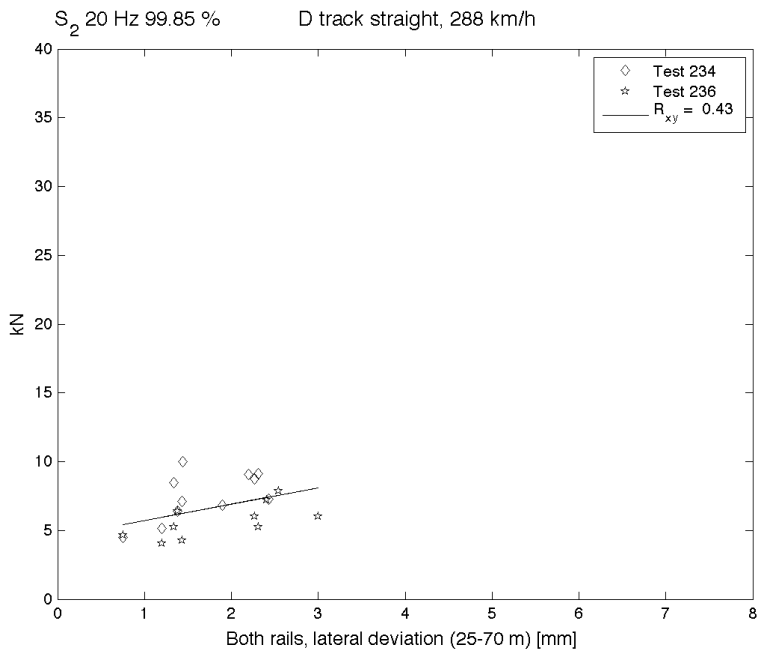


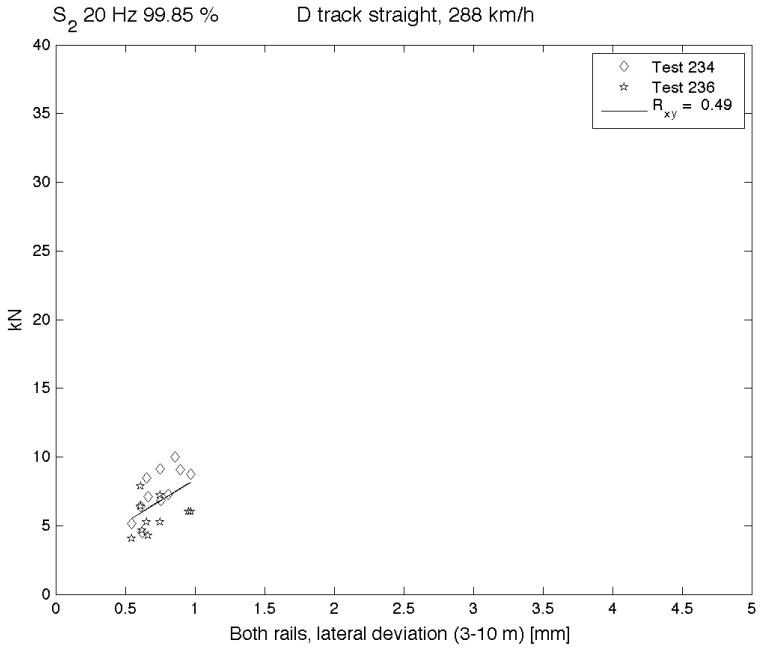

Q1X 20 Hz 99.85 %
Curves 900 < R < 1500 m, ay = 1.05- 1.29 m/s2
Test 252
Test 256
Test 257
Rxy = 0.57
kN
Outer rail, vertical deviation (10-25 m) [mm]

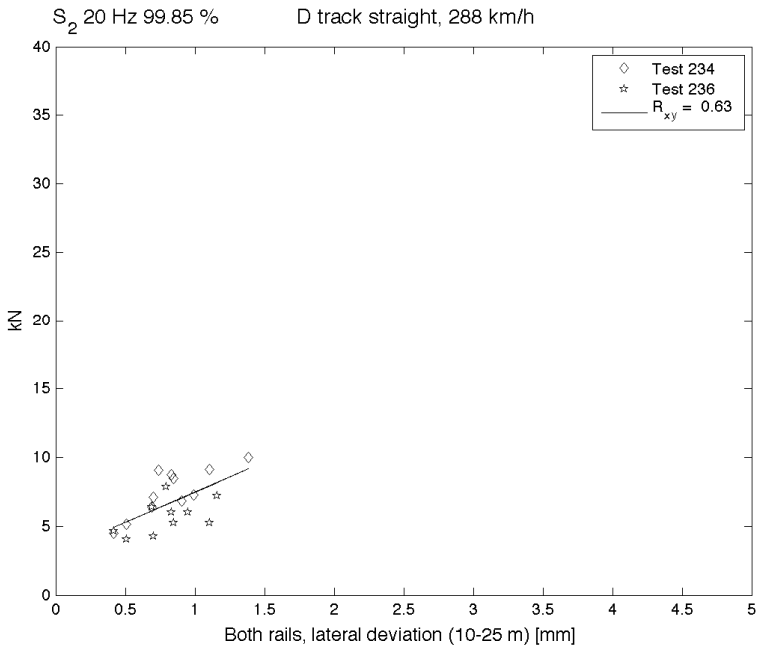

Q1X 20 Hz 99.85 %
Curves 900 < R < 1500 m, ay = 1.05- 1.29 m/s2
Test 252
Test 256
Test 257
Rxy = 0.73
kN
Outer rail, vertical deviation (25-70 m) [mm]

P – Forces vs. track irregularities – Straight Down-track S_2 20 Hz LP filter

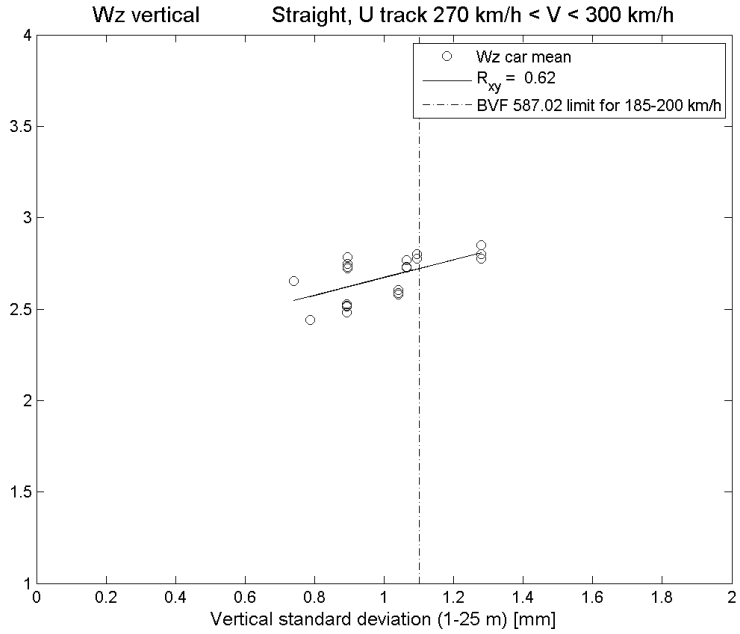


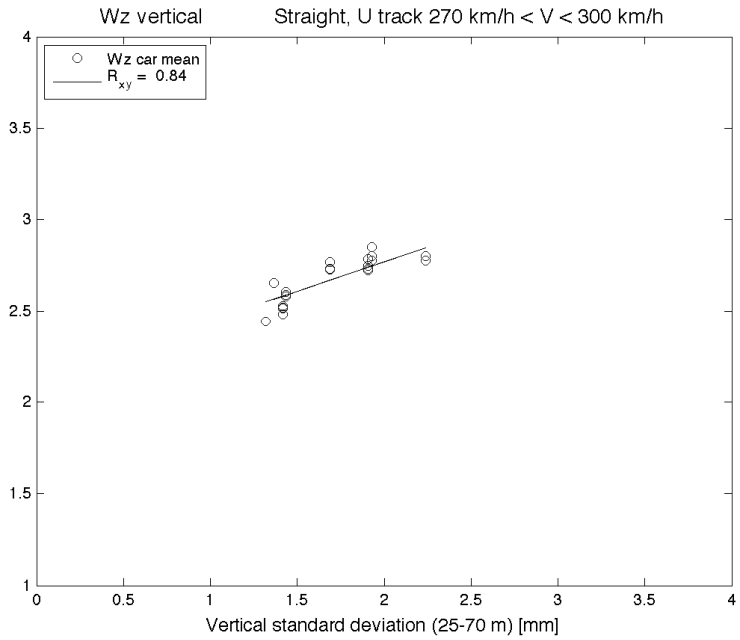


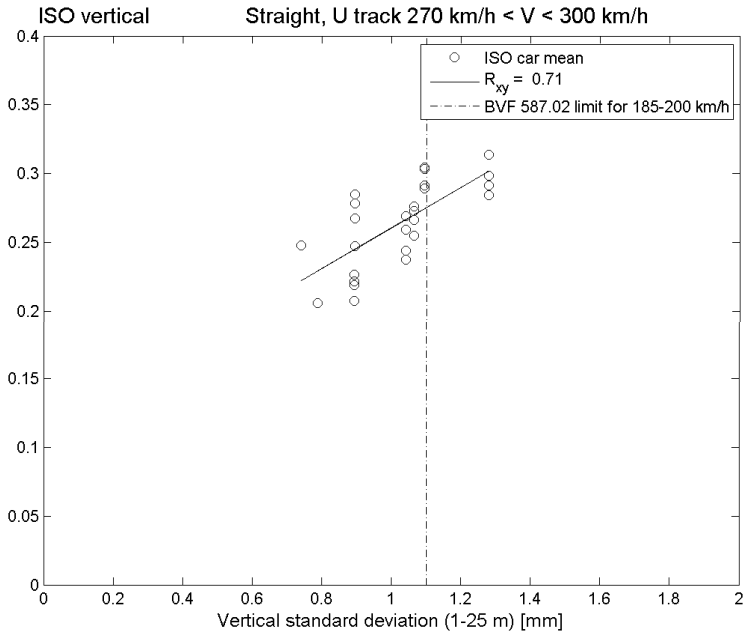

S2 20 Hz 99.85 %
D track straight, 288 km/h
Test 234
Test 236
Rxy = 0.49
kN
Both rails, lateral deviation (3-10 m) [mm]

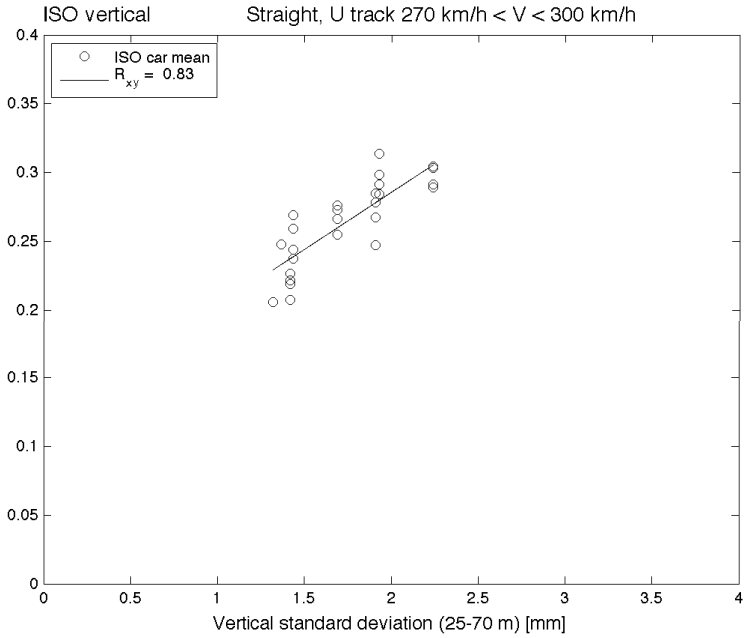

S2 20 Hz 99.85 %
D track straight, 288 km/h
Test 234
Test 236
Rxy = 0.63
kN
Both rails, lateral deviation (10-25 m) [mm]

Q – Comfort vs. track irregularities – Straight Up-track

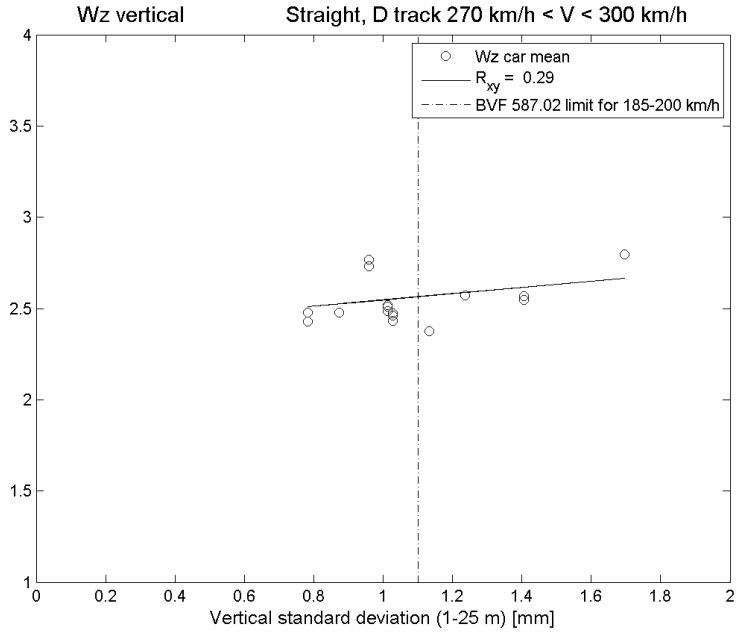


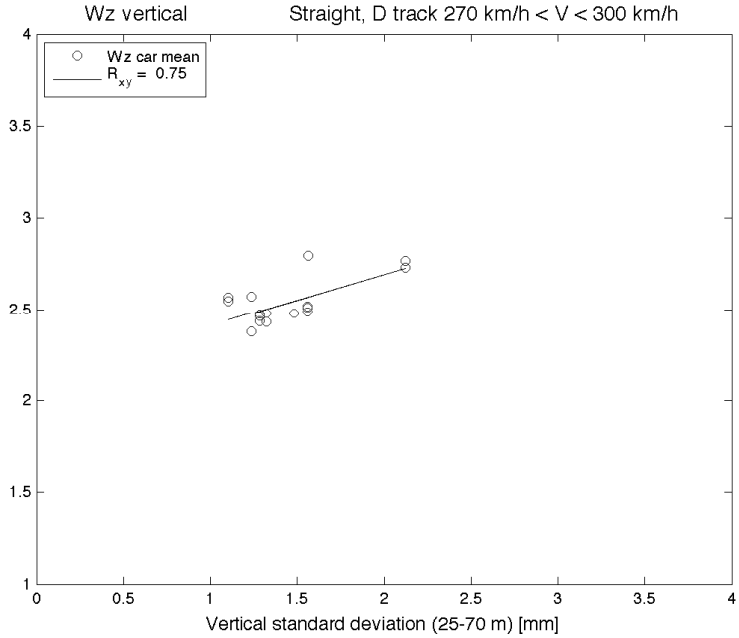


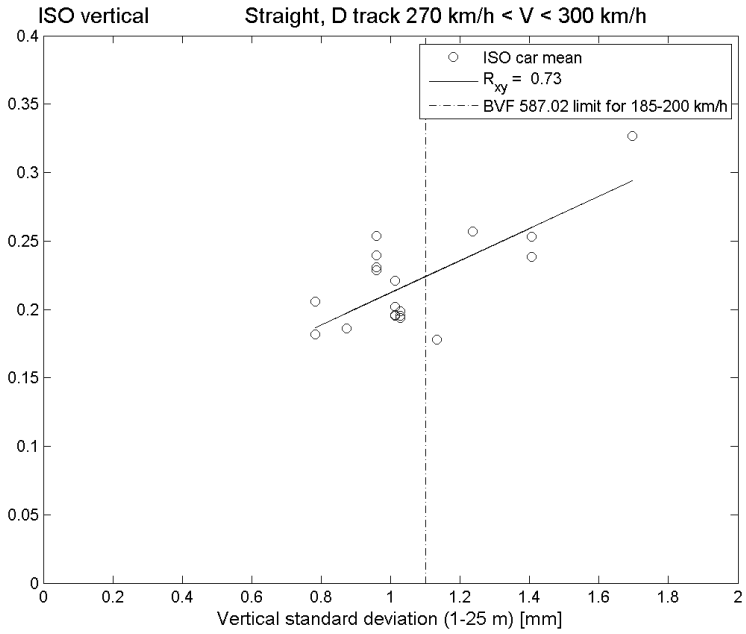

ISO vertical
Straight, U track 270 km/h < V < 300 km/h
ISO car mean
R_{xy} = 0.71
BVF 587.02 limit for 185-200 km/h
Vertical standard deviation (1-25 m) [mm]

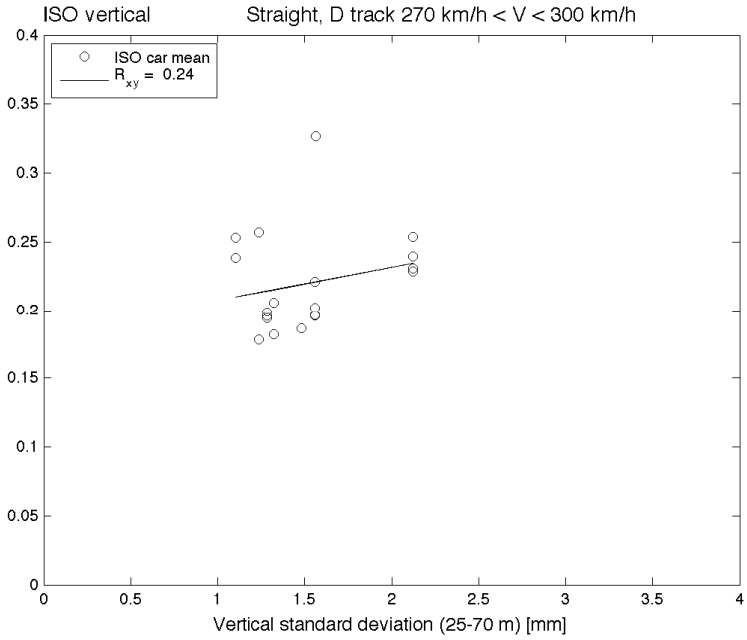

ISO vertical
Straight, U track 270 km/h < V < 300 km/h
ISO car mean
R_{xy} = 0.83
Vertical standard deviation (25-70 m) [mm]

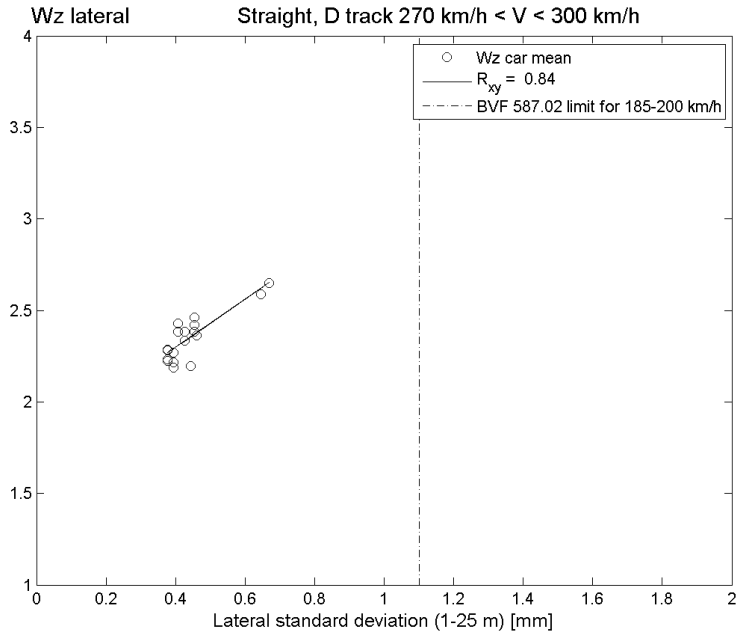
R – Comfort vs. track irregularities – Straight Down-track

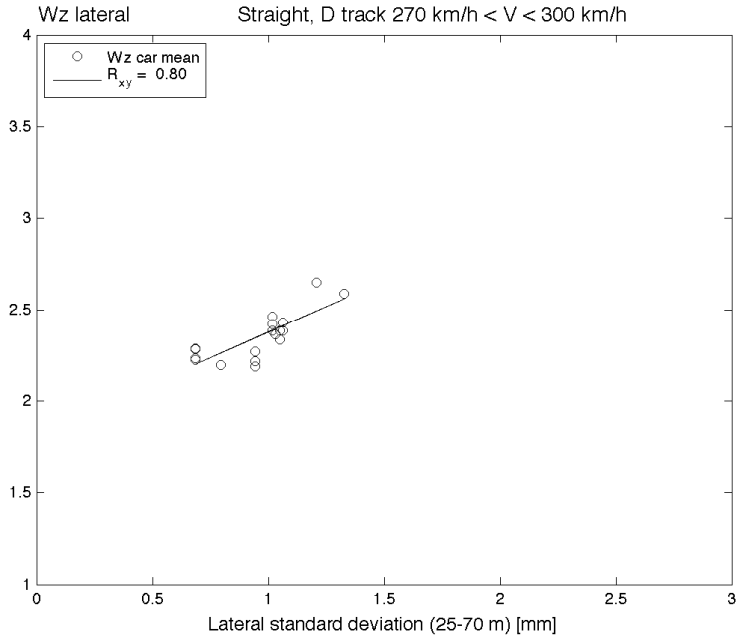


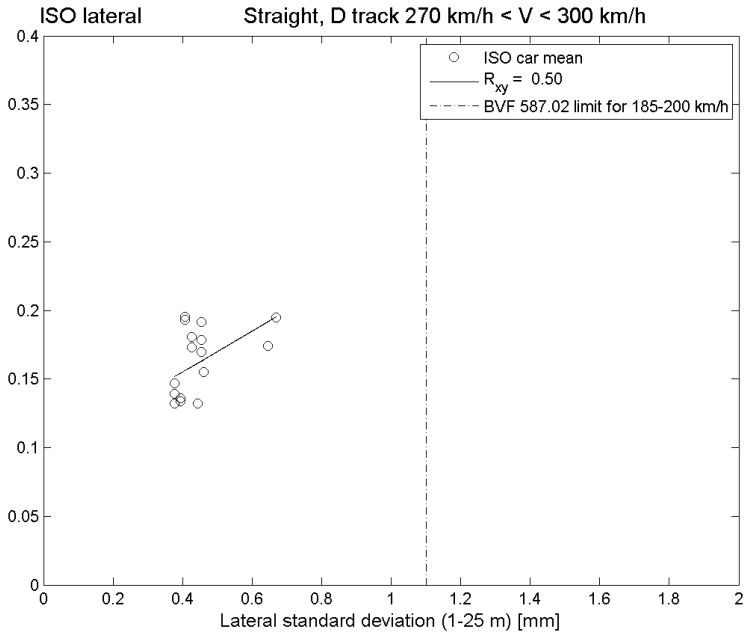


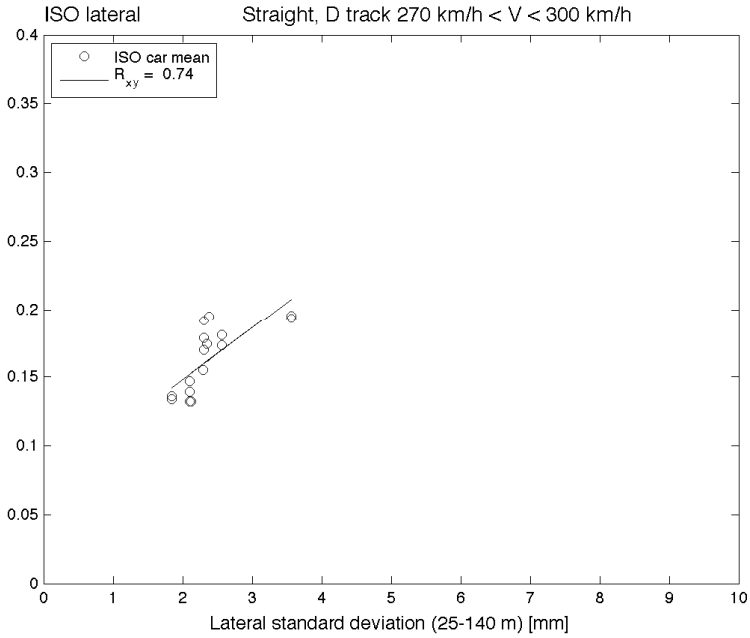

ISO vertical
Straight, D track 270 km/h < V < 300 km/h
ISO car mean
R_{xy} = 0.73
BVF 587.02 limit for 185-200 km/h
Vertical standard deviation (1-25 m) [mm]

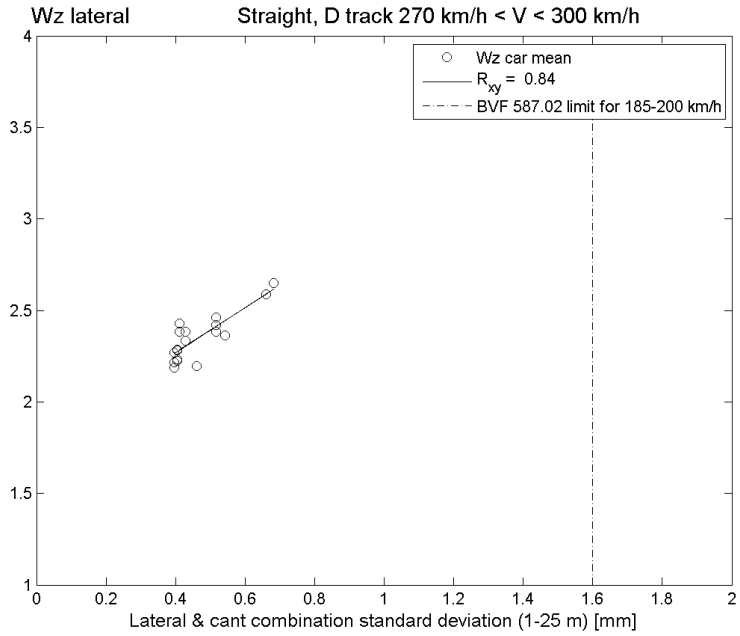

ISO vertical
Straight, D track 270 km/h < V < 300 km/h
ISO car mean
R_{xy} = 0.24
Vertical standard deviation (25-70 m) [mm]

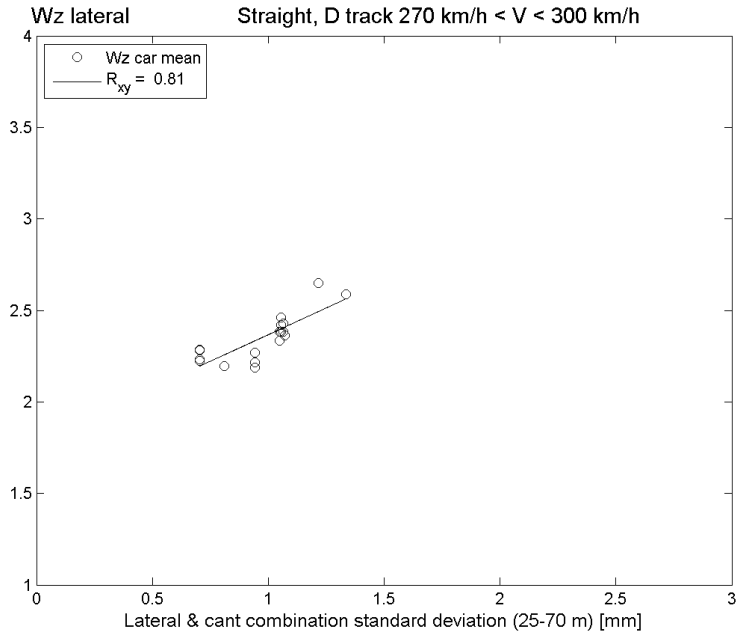

Wz lateral
Straight, D track 270 km/h < V < 300 km/h
Wz car mean
R_{xy} = 0.84
BVF 587.02 limit for 185-200 km/h
Lateral standard deviation (1-25 m) [mm]

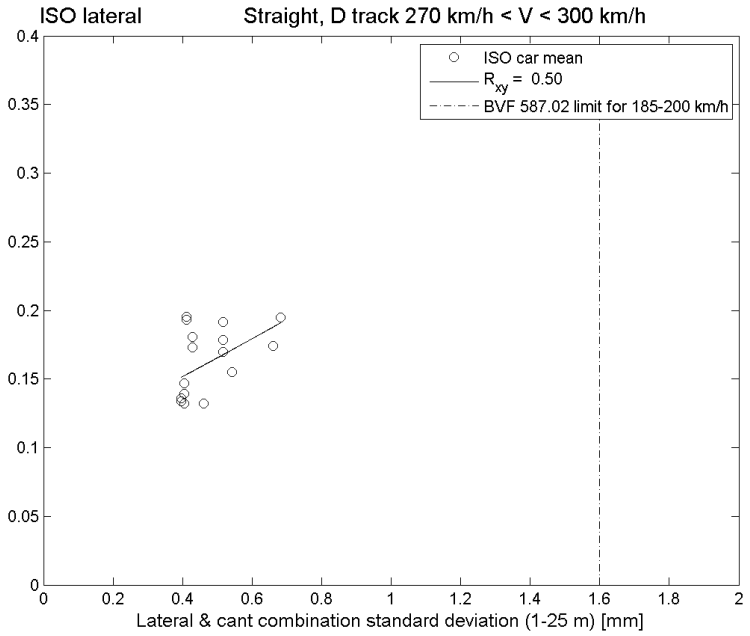

Wz lateral
Straight, D track 270 km/h < V < 300 km/h
Wz car mean
R_{xy} = 0.80
Lateral standard deviation (25-70 m) [mm]

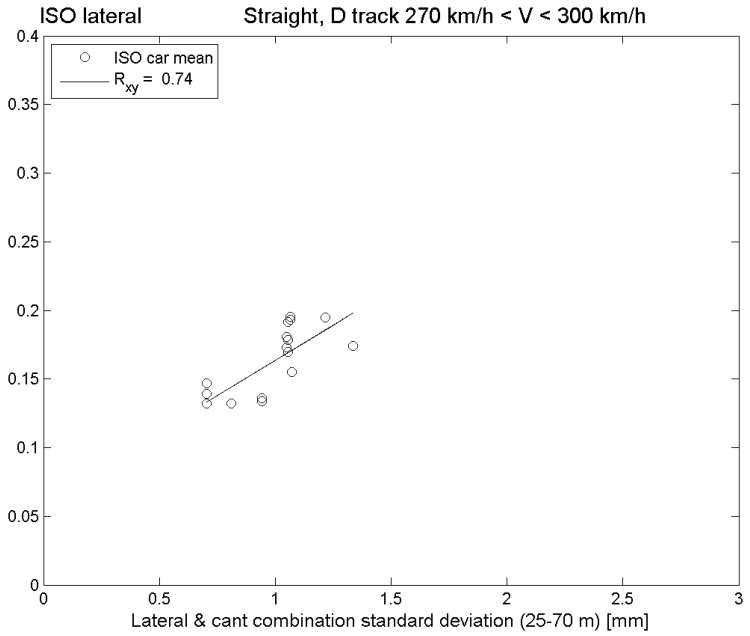

ISO lateral
Straight, D track 270 km/h < V < 300 km/h
ISO car mean
R_{xy} = 0.50
BVF 587.02 limit for 185-200 km/h
Lateral standard deviation (1-25 m) [mm]


ISO lateral
Straight, D track 270 km/h < V < 300 km/h
ISO car mean
R_{xy} = 0.74
Lateral standard deviation (25-140 m) [mm]

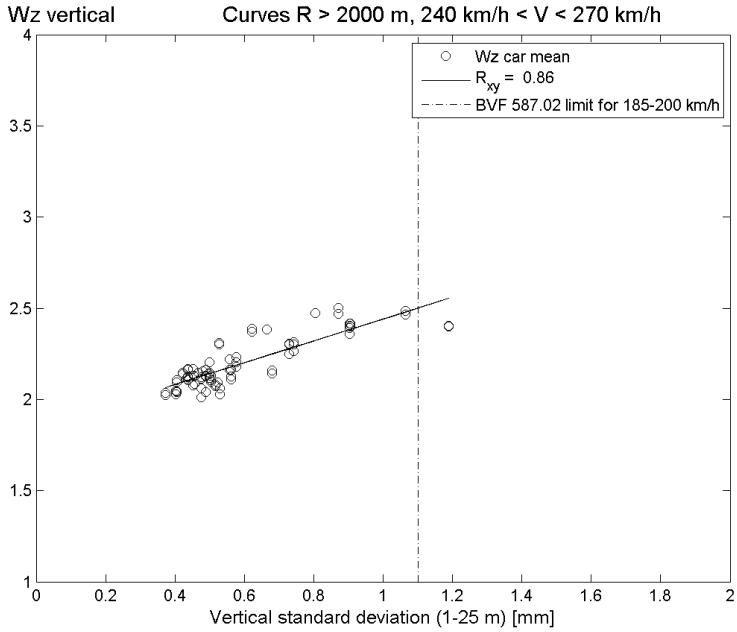

Wz lateral
Straight, D track 270 km/h < V < 300 km/h
Wz car mean
R_{xy} = 0.84
BVF 587.02 limit for 185-200 km/h
Lateral & cant combination standard deviation (1-25 m) [mm]

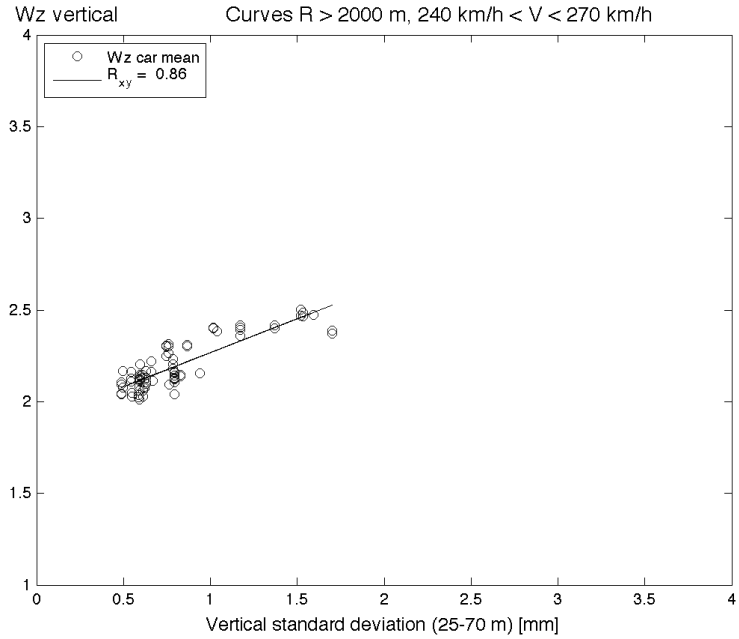

Wz lateral
Straight, D track 270 km/h < V < 300 km/h
Wz car mean
R_{xy} = 0.81
Lateral & cant combination standard deviation (25-70 m) [mm]

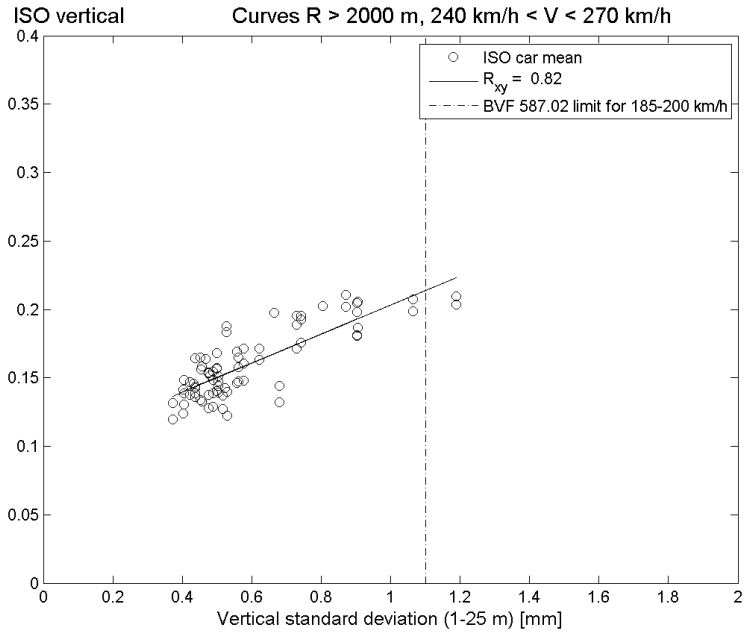

ISO lateral
Straight, D track 270 km/h < V < 300 km/h
ISO car mean
R_{xy} = 0.50
BVF 587.02 limit for 185-200 km/h
Lateral & cant combination standard deviation (1-25 m) [mm]

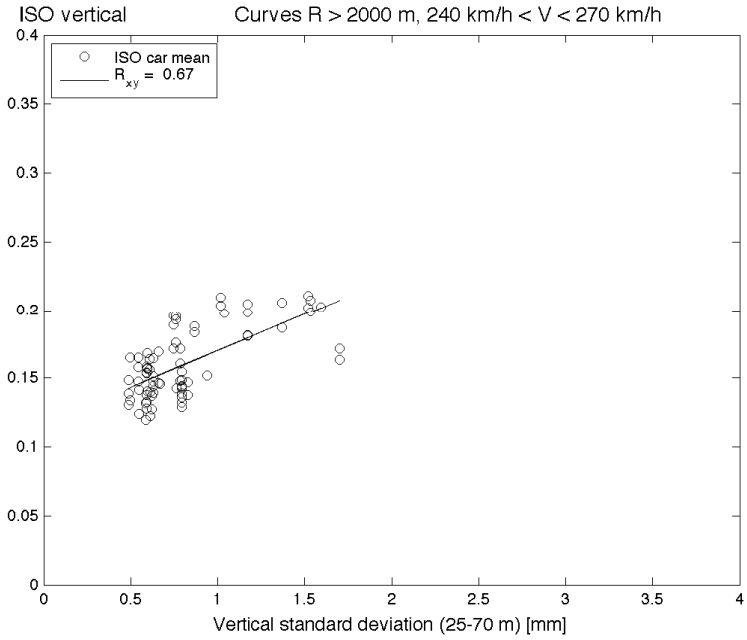

ISO lateral
Straight, D track 270 km/h < V < 300 km/h
ISO car mean
R_{xy} = 0.74
Lateral & cant combination standard deviation (25-70 m) [mm]

S – Comfort vs. track irregularities – Large radius curves

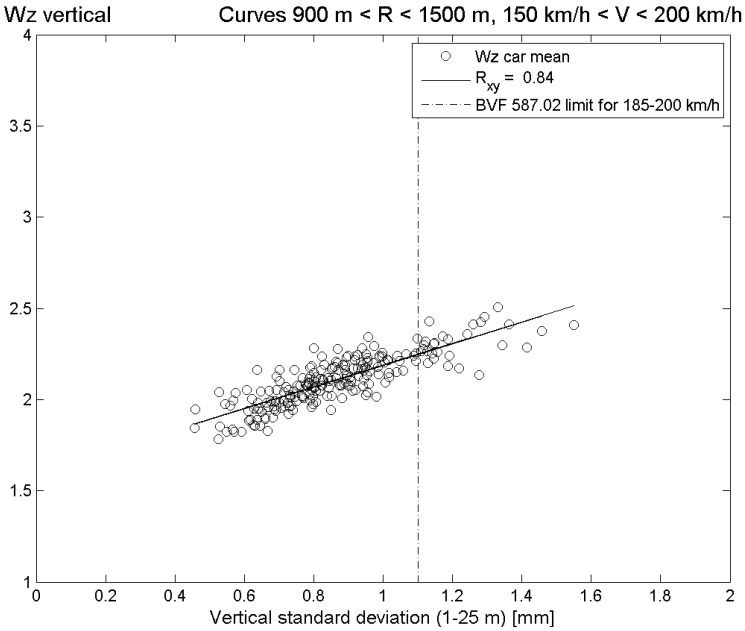


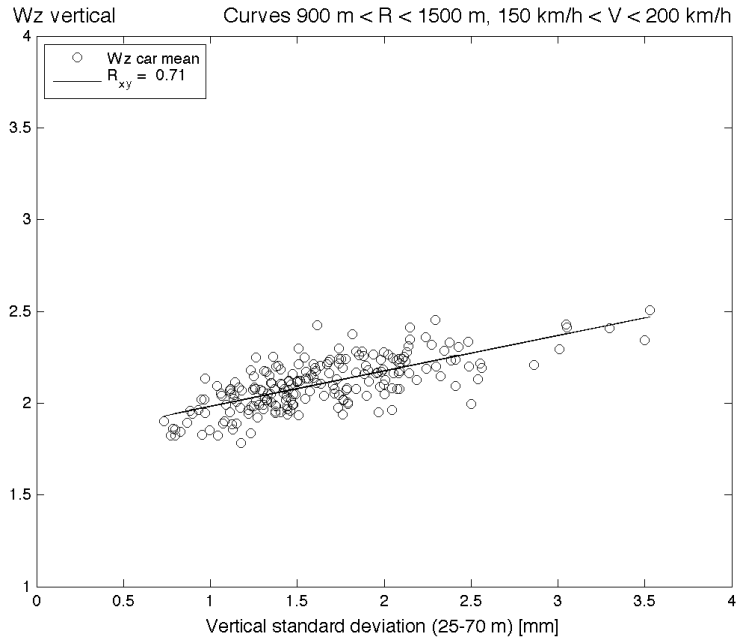


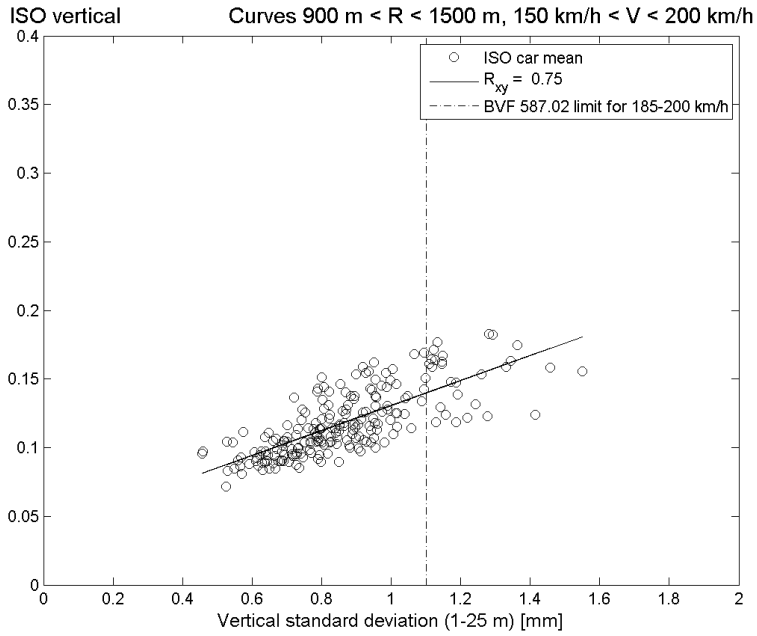

ISO vertical
Curves R > 2000 m, 240 km/h < V < 270 km/h
ISO car mean
R_{xy} = 0.82
BVF 587.02 limit for 185-200 km/h
Vertical standard deviation (1-25 m) [mm]

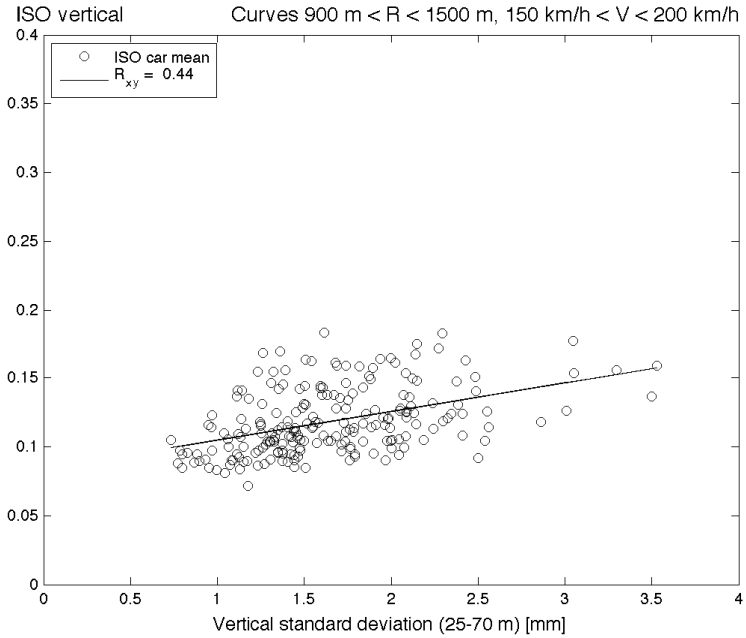

ISO vertical
Curves R > 2000 m, 240 km/h < V < 270 km/h
ISO car mean
R_{xy} = 0.67
Vertical standard deviation (25-70 m) [mm]

T – Comfort vs. track irregularities – Medium radius curves

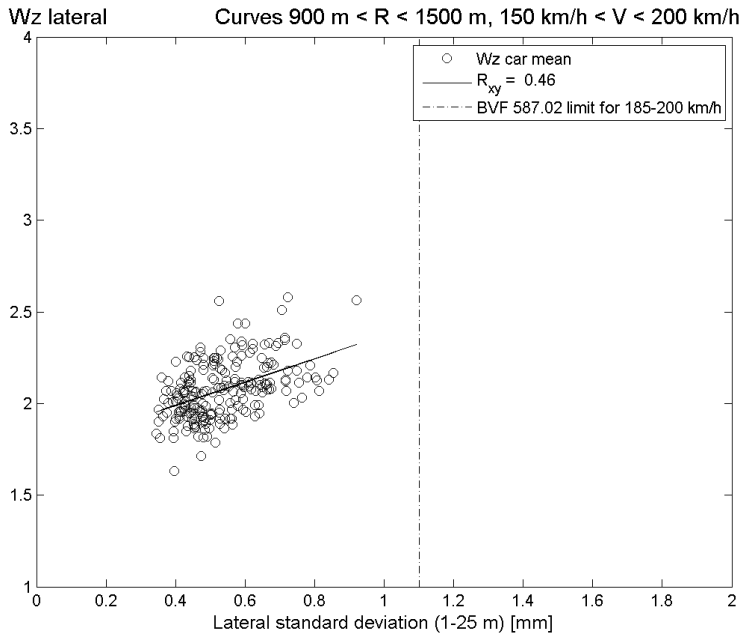


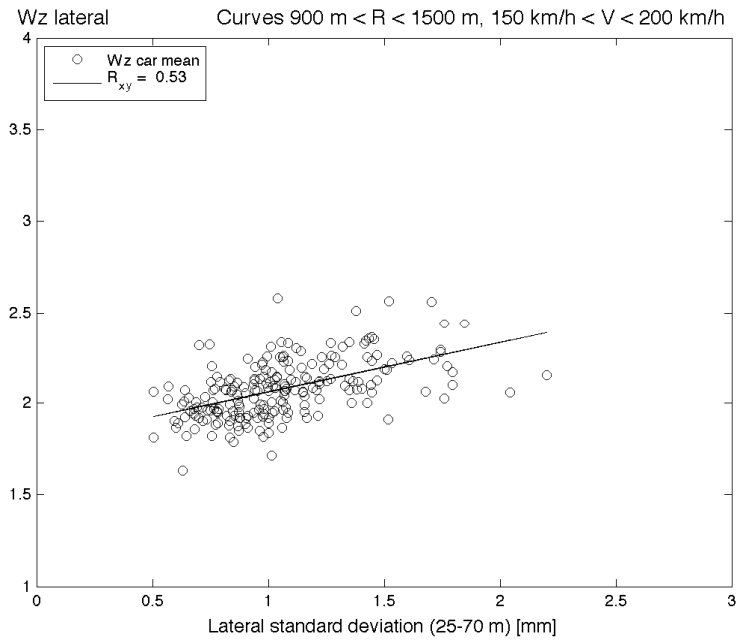


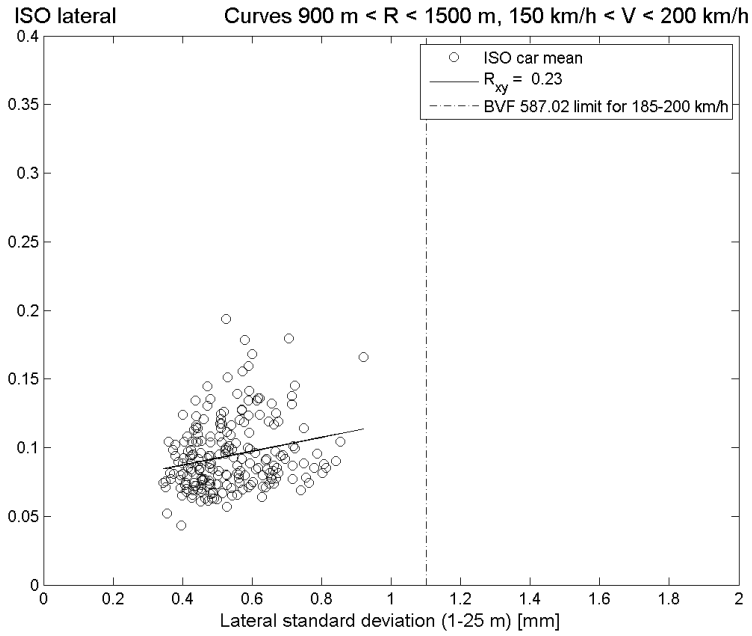

ISO vertical
Curves 900 m < R < 1500 m, 150 km/h < V < 200 km/h
ISO car mean
R_{xy} = 0.75
BVF 587.02 limit for 185-200 km/h
Vertical standard deviation (1-25 m) [mm]

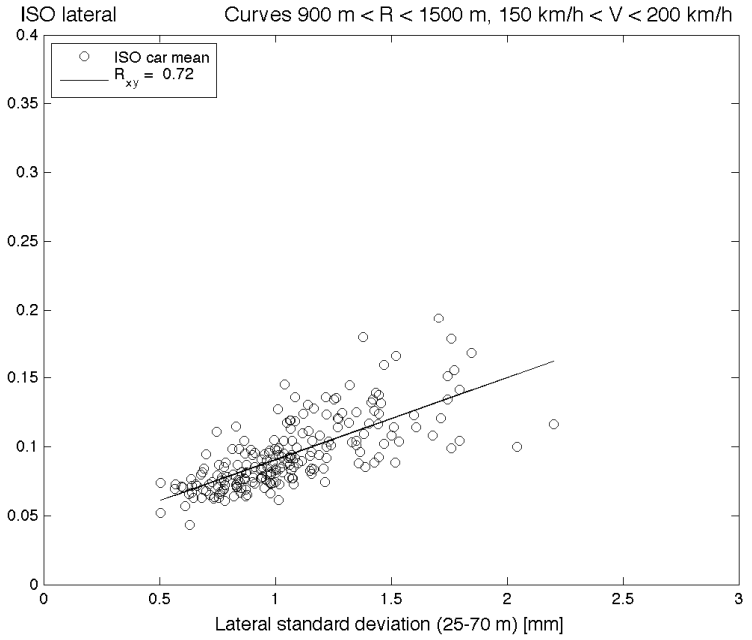

ISO vertical
Curves 900 m < R < 1500 m, 150 km/h < V < 200 km/h
ISO car mean
R_{xy} = 0.44
Vertical standard deviation (25-70 m) [mm]

T – Comfort vs. track irregularities –
Medium radius curves

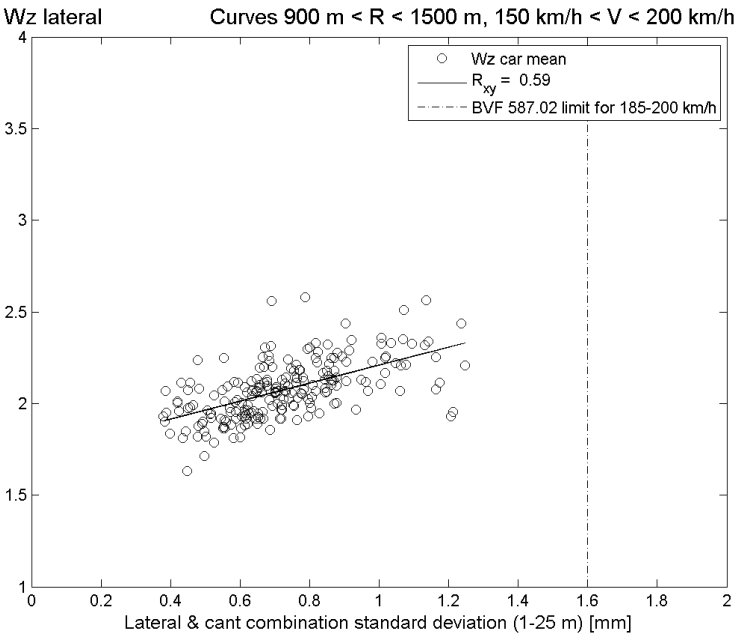


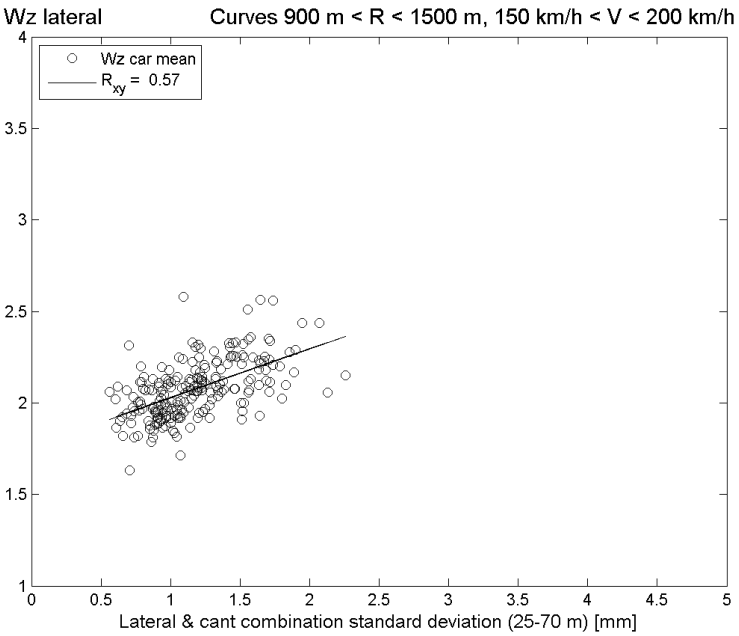


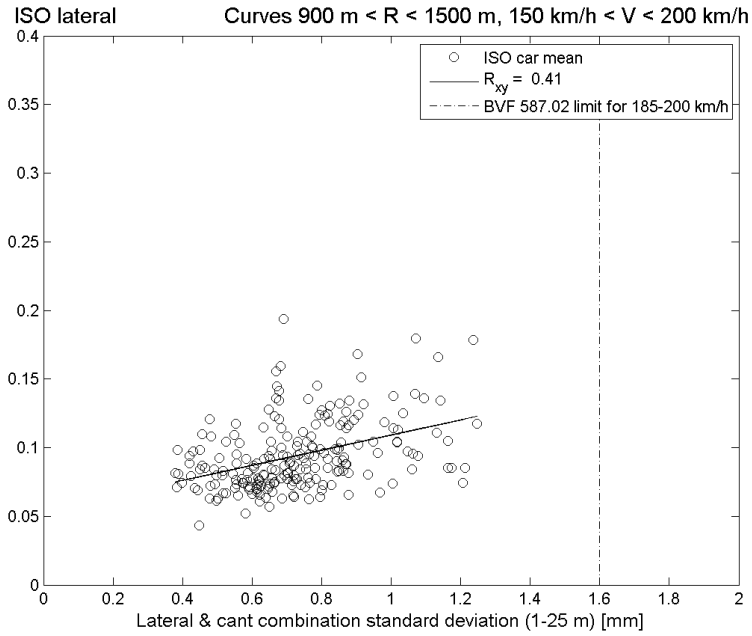

ISO lateral
Curves 900 m < R < 1500 m, 150 km/h < V < 200 km/h
ISO car mean
R_{xy} = 0.23
BVF 587.02 limit for 185-200 km/h
Lateral standard deviation (1-25 m) [mm]

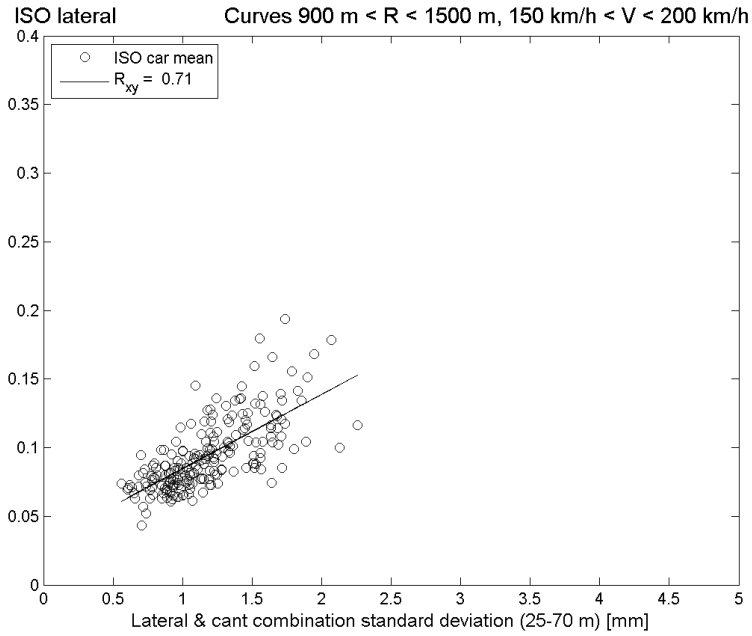

ISO lateral
Curves 900 m < R < 1500 m, 150 km/h < V < 200 km/h
ISO car mean
R_{xy} = 0.72
Lateral standard deviation (25-70 m) [mm]

T – Comfort vs. track irregularities –
Medium radius curves






ISO lateral
Curves 900 m < R < 1500 m, 150 km/h < V < 200 km/h
ISO car mean
R_{xy} = 0.41
BVF 587.02 limit for 185-200 km/h
Lateral & cant combination standard deviation (1-25 m) [mm]


ISO lateral
Curves 900 m < R < 1500 m, 150 km/h < V < 200 km/h
ISO car mean
R_{xy} = 0.71
Lateral & cant combination standard deviation (25-70 m) [mm]