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UIC comfort tests

Investigation of ride comfort and comfort disturbance on transition and circular curves

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Preface

During 1988 the Director of UIC High Speed Division, Mr Maraini, asked Mr Lauriks to organise a meeting to discuss the "Improvement of passenger train performances on conventional lines". This meeting resulted later in a working group called "UIC Comfort Group" to organise a test with a tilting train to investigate ride comfort and comfort disturbances on transition curves as well as on circular curves. Investigation on ride comfort on straight lines had been investigated by ERRI earlier.

The comfort test was then performed by Trenitalia with a Pendolino "Cisalpino" pre-series train from Alstom on the line between Firenze and Arezzo in October 2001. Trenitalia did the recordings of the measured data and a first evaluation. Main analysis was done by Mr J Evans and a second opinion on the analysis was done by Dr. J. Förstberg, VTI. Mr Lauriks wrote the main body of this report.

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The UIC working group started work on 07/10/1999
The work was completed on 16/01/2003.

Contents Page

Abbrivations and Notations **7**

1 Summary **9**
1.1 Requirements 9
1.1.1 History 9
1.1.2 Situation before the now completed tests 9
1.1.3 Remaining requirements 9
1.2 Origin of the work 9
1.3 Preparation of the tests 10
1.3.1 Characteristics of the potential participating trains 10
1.3.2 Results of the simulation 10
1.3.3 Test plan 10
1.4 Execution of the tests 10
1.5 Preparation of the data for analysis 11
1.6 Analysis 11
1.7 Validity of the conclusions 11
1.8 Conclusions 11
1.8.1 Consideration 11
1.8.2 Models 12

2 Purpose of the study **13**

3 What does comfort mean in the context of this report? **14**
3.1 Introduction 14
3.2 Comfort types 14
3.3 Comfort index 15
3.4 Comfort aspects 15
3.4.1 General 15
3.4.2 General aspects of passengers' comfort estimates 16
3.4.3 Influence of time 17

4 How comfort evolves with speed **18**
4.1 On straight track 18
4.2 On curved track 18
4.2.1 Non-tilting trains 18
4.2.2 Tilting trains 18

5 Elements of discomfort **19**
5.1 On straight track 19
5.2 On curved track 19
5.2.1 General definitions 19
5.2.2 Theoretical behaviour of those disturbing factors 22
5.2.3 Compensation of lateral acceleration discomfort in circular curves 23

6 Actual evaluation rules **26**
6.1 Evaluation of comfort on straight track 26
6.2 Evaluation of comfort on curved track 26
6.2.1 Comfort at curve transitions 26
6.2.2 Comfort at discrete events 27
6.3 Statistical interpretation of experimental results 27

6.3.1	General	27
6.3.2	Application in the case of comfort investigation	28
7	**Choice of the test zone**	**30**
7.1	Choice of the test route	30
7.1.1	Evaluation of the offered routes	30
7.2	Selection of Test Zones	31
7.3	Quality of the track in the test zone	33
8	**Description of the test**	**34**
8.1	The train	34
8.2	Main features of ETR 470.0	34
8.3	Measured parameters	34
8.3.1	Measured signals	34
8.3.2	Vote registration	35
8.3.3	Synchronisation between votes at different locations in the train	36
8.3.4	Synchronisation of the votes and the track sections to be judged	36
8.4	Test conditions	36
8.4.1	Route	36
8.4.2	Test runs	36
8.4.3	Test subjects	37
8.5	Registration of data, calculation of parameters	38
8.5.1	Method	38
8.5.2	Comment	38
8.6	Measurements for comfort	39
8.6.1	Location and type of sensors	39
8.6.2	Occupied places	40
9	**Possible influences of construction concepts of vehicle, track and/or system functioning on comfort**	**41**
9.1	Introduction	41
9.2	Basis for the examples in this chapter	41
9.3	Study of the car body angle	42
9.3.1	Influence of vehicle length	42
9.3.2	Influence of the flexibility of the suspension	42
9.4	Influence on lateral forces	43
9.4.1	Influence of the dynamic behaviour	43
9.4.2	Influence of length of the coach	44
9.4.3	Influence of position in coach	45
9.4.4	Additional discomfort due to functioning servo mechanisms	46
10	**General evaluation of local comfort results**	**47**
10.1	Evaluation of votes	47
10.1.1	Conclusions	48
10.1.2	Remark	48
10.2	Variation between groups	48
10.2.1	Significance of the difference	49
10.3	Seat position	50
10.4	Track elements	51
10.5	Evaluation of measured data	53

10.5.1	Transitions	53
11	**Evaluation of local comfort**	**60**
11.1	Analysis of Transition response	60
11.1.1	Types of transition	60
11.1.2	Test Conditions	60
11.1.3	Parameters	61
11.1.4	Scaling of votes	62
11.1.5	Examination of votes	62
11.1.6	Examination of data – simple transitions	62
11.1.7	Relationship between parameters – simple transitions	64
11.1.8	Regression analysis – simple transitions	68
11.1.9	Investigation of leading vehicle effects	72
11.1.10	Effect of other transition types	73
11.1.11	Non-linear regressions	78
11.1.12	Regression for track engineers	78
11.1.13	Contribution of diverse regression parameters	79
11.1.14	Estimation of group effect, knowing the regression model	81
11.1.15	Estimation of the residual influence of the position in the vehicle	84
11.1.16	Linear estimations of the test subjects	85
11.1.17	Study of the errors: Measured-Estimation	87
11.1.18	Conclusions on comfort in curve transitions	88
11.2	Analysis of Circular curves	88
11.2.1	Test Conditions	88
11.2.2	Parameters	89
11.2.3	Scaling of votes	89
11.2.4	Examination of data	89
11.2.5	Relationship between parameters	91
11.2.6	Regression analysis	92
11.2.7	Regressions with Reduced Dataset	95
11.2.8	Conclusion on comfort in circular curves	98
12	**Evaluation of average comfort**	**99**
12.1	Analysis of average comfort	99
12.1.1	Test Conditions	99
12.1.2	Parameters	99
12.1.3	Scaling of votes	100
12.1.4	Examination of data	100
12.1.5	Relationship between parameters	101
12.1.6	Regression analysis	104
12.2	Discussion of the results	107
12.2.1	Preliminary Conclusion	107
12.2.2	General quality of the regression	107
12.2.3	Spread of the errors	108
12.2.4	Average error per place in train.	108
12.2.5	Density of importance of each parameter	109
12.2.6	Cumulative importance of each parameter	109
12.2.7	Conclusions	109

13	**Conclusions**	**110**
13.1	Conditions	110
13.1.1	Environmental conditions of the tests	110
13.1.2	Extrapolation of results.	110
13.1.3	Calculation procedure	110
13.2	General impressions on the quality	110
13.2.1	The comfort evaluation is linear in the conditions covered by the tests	110
13.2.2	The description of the comfort is sufficiently good to describe the comfort differences due to the seat position	110
13.3	Conclusions in relationship with the organisation of tests	111
13.3.1	Choice of the test track	111
13.3.2	Choice of the test vehicle	111
13.3.3	Choice of place in the coach	111
13.3.4	Synchronisation	111
13.3.5	Nature of the databases	111
13.3.6	Number of events in the experimental database	111
13.4	Interpretation of the results	111
13.4.1	Many parameters are correlated	111
13.4.2	Parameters representing shorter events do give better statistical results	112
13.4.3	The spread of the votes is considerable	112
13.4.4	The individual influences are well defined by their associated *t*-parameters	112
13.5	Influence of construction details	112
13.5.1	Influence of the length of the transition	112
13.5.2	Influence of the length of the vehicle	112
13.5.3	Influence of the control of the tilting system	112
13.5.4	Influence of compensation rate	113
13.5.5	Influence of train speed	113
13.6	Global impressions of the comfort influences	113
13.6.1	Track and train used in test were of excellent quality	113
13.6.2	Maximum values give best comfort description	113
13.6.3	Influence of lateral acceleration remains dominant	113
13.6.4	Influence of rotational acceleration is significant	113
13.7	Proposed evaluation procedure	113
13.7.1	Evaluation of local comfort on curve transitions	114
13.7.2	Evaluation procedure for local comfort, optimised for track engineers	114
13.7.3	Evaluation of local comfort in circular curves	115
13.7.4	Evaluation of average comfort	115
14	**References**	**116**

Appendices 1–3

Abbrivations and Notations

AEAT	AEA Technology Rail, a British consultant company
DBAG	Deutsche Bahn AG
ERRI	European Rail Research Institute
FS Trenitalia	Italian Railways
JBV	Jernbaneverket, Norway National Rail Administration
SNCB	Belgian National Railway
UIC	International Railway Union
VTI	Swedish National Road and Transport Research Institute

Notations

NCA	Non compensated acceleration (i.e. lateral acceleration in track plane)
N_{MV}	Ride comfort evaluation according to CEN 12299, mean value
N_{VA}	Ride comfort evaluation according to CEN 12299, seated passeneger
N'va	5 s evaluation according to the N_{VA}
N_{VD}	Ride comfort evaluation according to CEN 12299, standing passeneger
P_{CT}	Passenger dissatisfaction on cure transition
P_{DE}	Passenger dissatisfaction on discrete events

1 Summary

1.1 Requirements

1.1.1 History

The ERRI B153 committee undertook a number of studies on ride comfort, but always comfort (seated and standing) on mainly straight track. Therefore the conclusions from this work (N_{VA} and N_{MV}) cannot be used without verification for a journey on a track with a high number of curves. Extrapolation from multiple regression analysis is not allowed.

The CEN standard (ENV 12299:1999) includes procedures for the evaluation of local comfort on curve entry transitions (P_{CT}) and at discrete events on circular curves (P_{DE}). However, the conditions in normal commercial operation are such that these measures do not give convincing results because the level of the accelerations is not sufficiently high.

The ERRI B207 committee carried out ride comfort tests on curved track, but the results were inconclusive due to problems with the test data.

1.1.2 Situation before the now completed tests

- The existing procedures N_{VA} and N_{MV} are not applicable on track containing a relatively high number of curves.
- The P_{DE} and P_{CT} methods deal only with local comfort and are only valid in a relatively high acceleration environment.

1.1.3 Remaining requirements

Specialists were convinced that the following research should be done:

- Study of local comfort in circular curves and curve transitions, in order to guide the construction of track and trains.
- Study of the average comfort on track with a high number of curves in order to be able to appreciate the global influence of different track and vehicle parameters on comfort.
- Study of the provocation of nausea, phenomena that limit the full use of the capabilities of tilting trains.

1.2 Origin of the work

The work was first proposed by the high-speed division of UIC, and taken over by the working group "Improvement of passenger train performance on conventional lines". The idea was that it should be possible to improve the commercial speed on a given line, without too much investigation. One possibility was to increase the speed in curves without taking any other action, which will increase the lateral acceleration experienced by the passengers. Increasing the cant in circular curves was also a solution, using tilting train bodies was a supplementary possibility. What are the supplementary constraints on the passengers? The centrifugal forces are more balanced during the ride on the circular curve, but in the transition, a number of phenomena appear, and degrade comfort. On some occasions we know that onset of nausea can occur.

The original testing procedure proposed by the working group asked for experiments in two countries, but this was so expensive that UIC could not agree with the proposal. As a compromise UIC agreed with one test series on a carefully chosen test track with a minimum of test persons. Numerical simulations should facilitate the choice. However it is clear that while simulation helps to a certain extent, the consequences of this choice inevitably reduce the robustness of the results.

1.3 Preparation of the tests

1.3.1 Characteristics of the potential participating trains

Three companies were asked to deliver numerical characteristics of the most recent trains in service, under strictly confidential conditions, to allow the working group to undertake simulations as a preparation for the tests.

One manufacturer refused, a second manufacturer delivered rather general characteristics. A last manufacturer delivered an add-on module, to make simulation possible. Because of the attitude of the first manufacturer, the remaining possibilities of test journeys were reduced to two administrations.

1.3.2 Results of the simulation

Two series of simulations were executed, giving information on the roll speed, the jerk and the lateral acceleration on the passenger on each of the two remaining test journeys. The results were sufficiently accurate for choosing an appropriate test track, but not for the forecasting of the comfort, as some essential information were not present in the furnished models.

Both of the proposed test journeys were acceptable. Considering both the availability of data and constraints on the availability of the test train, the journey Firenze-Arezzo from FS-Trenitalia was chosen as the solution.

A second series of simulations with the proposed test train on this journey was used to guide the selection of local events to be evaluated on each test run, in order to assure the largest possible experimental basis for the statistical analysis of the tests. 15 simple curve entry transitions and 9 plain curves were chosen, together with some other kinds of transition (4 reverse transitions, 4 adjacent transitions, 3 compound transitions and 1 short curve). The results of the test confirmed the choices made.

1.3.3 Test plan

Testing was planned to last for one week. Two days were needed for tests of local comfort and two days for the evaluation of average comfort. One spare day was planned to allow any failed tests to be repeated or to execute complementary situations.

The journey firenze-arezzo-firenze was to be executed two times a day. This would give a maximum of 15 transitions * 2 days * 2 directions* 2 runs * 5 groups = 600 data cases for local comfort, and 8 five-minute zones * 2 days * 2 runs * 2 directions = 64 independent data cases for average comfort.

1.4 Execution of the tests

The tests were executed as planned.

This test plan proved sufficient for local comfort. For the evaluation of average comfort, it was found that the chosen test plan gave only a minimal number of data cases. The exclusive use of good track and good quality coaches resulted in a rather small spread of input data, making it difficult to obtain good regressions.

1.5 Preparation of the data for analysis

It was not possible to obtain the time history of the recorded test signals. So the working group was obliged to propose procedures to calculate the value of a number of parameters expected to be part of a successful comfort evaluation model. The calculation of the potential parameters was been undertaken by trenitalia. The calculation has been adapted a few times, to correspond best with the needs of the statistical analysis.

Two series of parameters were calculated, one for local comfort and one for average comfort.

1.6 Analysis

Three series of statistical analysis were undertaken.

- Local comfort in curve transitions;
- Local comfort in circular curves;
- Average comfort.

For each of the cases a number of models were tested with the help of multiple linear regression techniques. In principle the best solution has been proposed, but the maximum is rather broad, so that the choice seems not to be critical and for well described reasons a “close to optimal mathematical solution” has been chosen.

1.7 Validity of the conclusions

The correlation of the regressions is somewhat disappointing, but understandable, giving the relatively small number of experimental data and the high spread of individual votes. But the parameters with an influence on comfort all have more than sufficient statistical confirmation.

The experiments were executed on good quality track with the help of a good quality train on a journey containing a high number of circular curves and curve transitions. This restricts the comfort evaluations to this kind of quality of train and this kind of quality of journey. These restrictions are in agreement with the purpose of the study. Due to the large experimental database there are no other restrictions to the use of the proposed evaluation method.

1.8 Conclusions

1.8.1 Consideration

The conclusions do contain an important number of considerations, helping to understand the meaning of the different models, and the circumstances permitting their use.

The conclusions also contain advice for the organisation of new tests, and for the construction of trains and track.

1.8.2 Models

Three different models are proposed, corresponding to the best possible description for the phenomena.

- Model 1 proposes an estimation procedure for comfort in transition curves,
- Model 2 proposes an estimation procedure for comfort in circular curves,
- Model 3 proposes an estimation procedure for the average comfort during a ride on a track containing a relatively high number of curves.

In addition a fourth model is proposed for the convenience of track engineers developing transition curves.

All these models can be used either as models evaluating comfort in a real situation, or as models offering guidance to track and vehicle engineers during the design process.

2 Purpose of the study

ISO 2631 is an international standard that gives methods and procedures for the assessment of vibration comfort. This standard has a broad range of applications.

As a consequence of the unique environment in railway situations, it was necessary to describe how this standard could be applied in railway practice.

The ERRI committees B153 and 207 were charged with investigating the application of the standard on railways, taking into account the railway practice of comfort estimation. The committees have published a number of reports. The most important result was a proposal for the evaluation of comfort, using a method agreed by UIC.

Because of the methods used to conduct these studies, the resulting proposal is, in a strict sense, only valid for straight lines.

In the meantime, railway manufacturers have started to build tilting coaches, and the overall speed of railway operation has increased, so that the proposed formulae for comfort evaluation are no longer valid in these circumstances.

In parallel with the work of committees B153 and B207, the former British Rail Research started investigation on comfort in tilting trains. Their published results are of great interest for those companies using tilting coaches in trains.

However, the results of that study are most valid in lower comfort environments, which posed some doubts on their utilisation for comfortable trains as they are actually put in service.

During this study also the European community also published a standard (CEN ENV 12299) mentioning all 'recent' European work in this area. The conclusions of all the former studies are integrated in this European standard. However the evaluation rules valid for straight track and the evaluation rules published for travel on circular curves and in curve transitions are not mutually complementary for a number of reasons further explained in this report.

The UIC constituted a working group to investigate the existing rules on curved track using trains of good quality, and to propose a unique homogenous UIC comfort evaluation model that would also be valid for this kind of operation.

After UIC agreement with the work, it is the aim to introduce the evaluating models into the UIC 513 leaflet and into the appropriate CEN standard

A second major constraint, due to low frequency motions in trains, is the possibility of provocation of nausea. This phenomenon is not a subject of this study.

3 What does comfort mean in the context of this report?

3.1 Introduction

Comfort is often defined as the well-being of a person or absence of mechanical disturbance in relation to the induced environment. This well-being can be achieved and also disturbed by very different factors, both physiological (expectation, individual sensitivity, etc.) and by physical environment (motions, temperature, noise, seating characteristics, etc.). For these reasons, the same values of vibration might be judged uncomfortable in one environment and acceptable in another.

Ride Quality is an entity representing the passengers' judgement of quality of the ride (whole subjective experience including motion environment and associated factors). It can be limited to consider only motion environments (from ISO Standard 5805).

In our case we have used the word "comfort" in this sense – the subjects' opinion on the ride comfort (ride quality) on a given scale.

However, there is a quite different acceptance of good comfort for a short ride on bus, tram or commuter train, a medium distance ride on a regional train or a long distance ride on an inter-city train.

3.2 Comfort types

We make a distinction between two types of comfort: average comfort and local comfort. The measures listed below are defined in the CEN standard ENV12299.

Average comfort

This is an evaluation of passengers' opinions of the comfort during the previous 5-minute ride. Defined comfort criteria are: [N_{VA}, N_{VD} *and* N_{MV}].

In principle, average comfort can be assessed for all types of track, but the existing measures are only valid for mainly straight track.

Local comfort

Local comfort assess comfort in local situations over a period of a maximum of a few seconds. Defined criteria are: [P_{CT}] Comfort on Curve Transitions and [P_{DE}]. Comfort in respect of Discrete Events Local comfort can be used to describe behaviour on points and crossings, curve transitions and circular curves (this is a non-obligatory proposal in the CEN standard).

It is important to remember that the different comfort qualifiers in the standard use different definitions of comfort and that they have as a consequence different (overlapping) domains of application.

NOTE

The methods used in this report study the influence of the judgement of people on their comfort feelings while travelling in railway coaches, in the given circumstances. The methods do not give information on the behaviour of the coaches.

3.3 Comfort index

A comfort index in our report is the expression of the average opinion of passengers of their ride comfort as stated in their replies to a precise question that incorporates a given comfort scale.

Only if this precise definition is used does comfort becomes a useful tool for the study of the interaction between motion environments in the coaches and passengers during a train journey.

This means that the resulting comfort evaluation method depends on the kind of situations offered to the test subjects. Until now, most of the comfort tests done for the UIC by ERRI research groups did not incorporate curves, and as a consequence journeys incorporating a significant number of curves can not be evaluated by existing procedures.

3.4 Comfort aspects

3.4.1 General

In most cases, the comfort level is shown on the y-axis and the vibration quantifier on the x-axis. Good comfort is generally in the lower part of the graph and poor comfort in the upper part.

The vertical variation of the comfort level is limited, but the vibration level on the x-axis can begin at zero and rise to very high values. The average opinion of passengers ranges between the two lines shown on this slide.

For practical reasons, the zone between poor comfort and perfect comfort is divided into a number of sub-zones.

In general there is a rather steep transition from the bottom line to the top line. The transition is close to a straight line, rounded at the end by border effects.

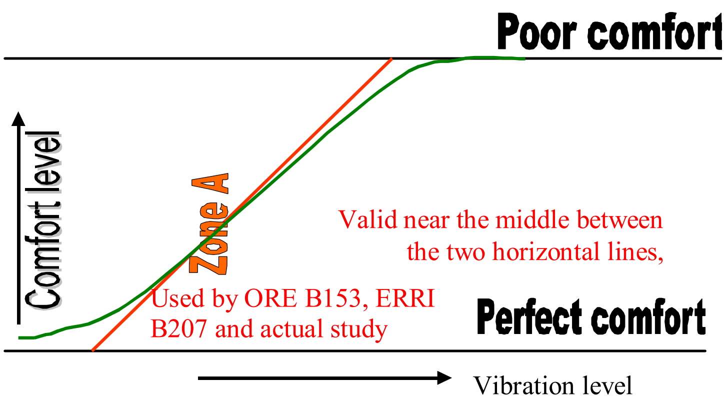


Figure 3-1 *Relation between vibration level and comfort level. Most of the time, comfort in real situations is situated in the central zone (zone A), at some distance from the boundaries.*

Representation of passengers' opinions in zone A

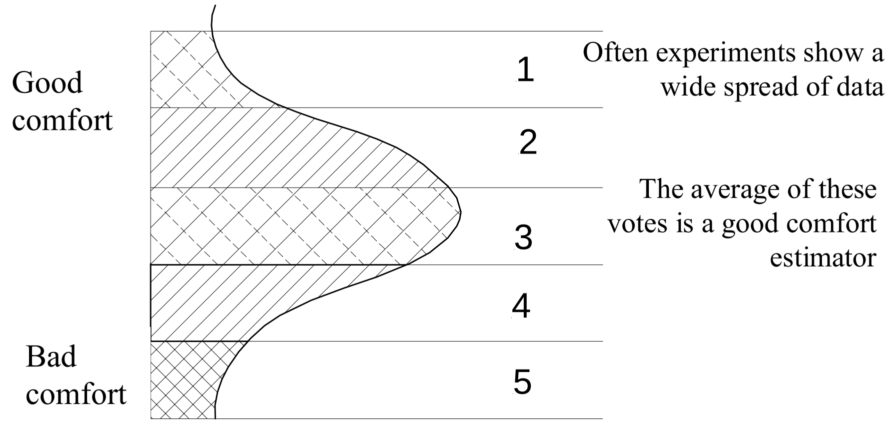


Figure 3-2 A representation of passengers' estimation of comfort. Their votes are spread over a number of classes.

Each person may have a different opinion of a situation. Experiments often show a wide spread of data. Each horizontal zone in the previous diagram has a number of votes.

The average of these votes is a good comfort estimator near the middle between the two horizontal lines. This method is used by ORE B153 for describing mean comfort in the seated position on straight track.

3.4.2 General aspects of passengers' comfort estimates

For situations near the upper boundary of the graph, where comfort is poor, it is better to use a different approach.

When passengers express their opinion in poor comfort situations, they are not able to use stronger words than 'I disagree'.

So, if we want to investigate the upper zone, symbolised by zone B another statistical parameter is needed. Instead of using the average, the relative number of passengers who stated disagreement with the level of comfort experienced is used. This approach near zone B is used for the P_{CT} evaluation in curve transitions and P_{DE} evaluation for discrete events in circular curves.

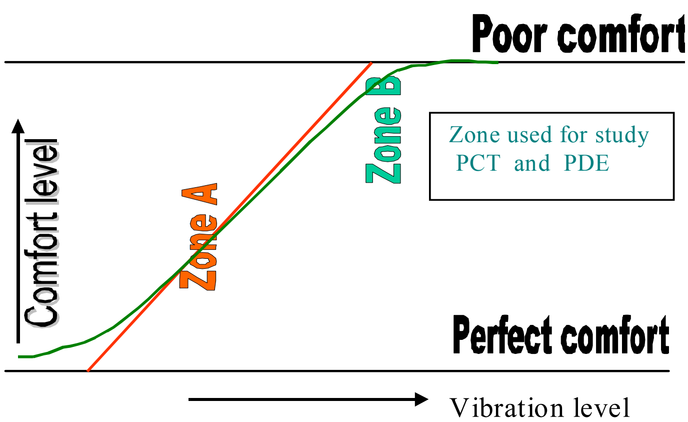


Figure 3-3 Relation between vibration levels and comfort level, showing the zone B position.

Representation of passengers' opinions in zone B

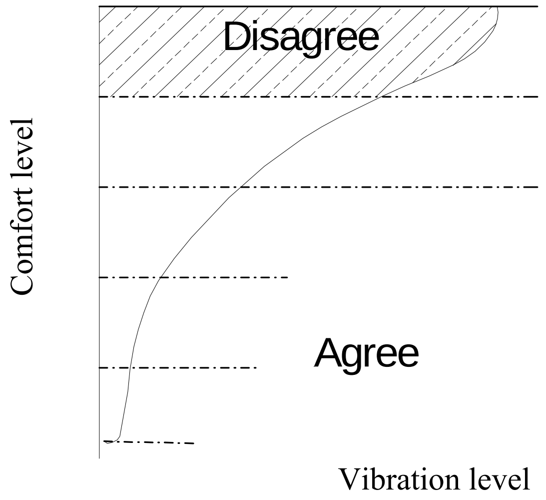


Figure 3-4 *Relation between vibration level and discomfort in zone B.*

Zone B should not exist in commercial service.

3.4.3 Influence of time

It is not possible to demonstrate the influence of time on average comfort on long-distance trains, even after experiments spanning a three-hour period. Comfort remains a question of the immediate past.

However, people do remember the highest vibration levels in the zone tested. Therefore a special statistical procedure calculates 95% levels for each of the important vibration inputs. A 95% value is used instead of a maximum value to ensure sufficiently reliable results. Consequently, improvements in track quality must result in very constant quality. The worst zone determines the quality level.

4 How comfort evolves with speed

4.1 On straight track

There is only a slight increase in the vibration level due to imperfections in the track; the slope of the estimator depends on the characteristics of the coach suspension and track irregularities.

4.2 On curved track

4.2.1 Non-tilting trains

The maximum speed of the train is limited by the network administrations with a maximum *NCA*. Because track cant is limited, the quasi-static lateral acceleration must be higher in curves and therefore there is a change of the level of lateral acceleration (jerk) in curve transitions. Moreover it is evident that the roll angle of the coach will change in curves. All these factors cause deterioration in comfort.

4.2.2 Tilting trains

Lateral acceleration may be lower with artificial tilting by comparison with a situation without tilting, but the roll angle/velocity of the coach is even higher. Moreover, due to imperfections of the tilting control system the tilting system may operate too late or too soon, causing more uncompensated lateral acceleration and jerk.

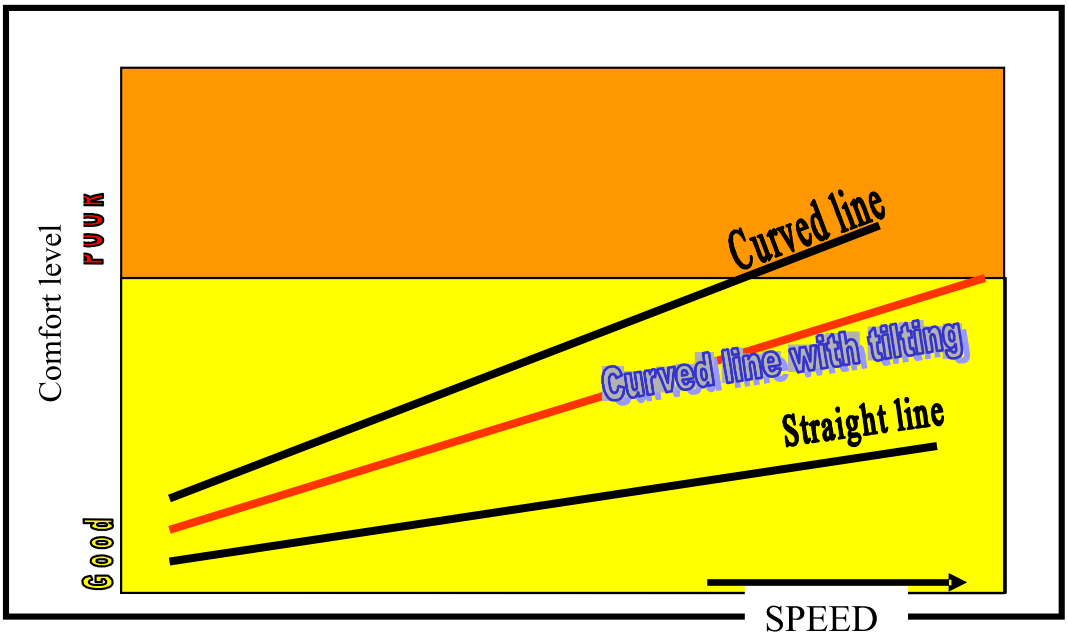


Figure 4-1 *Ride comfort levels detoriates with speed depending on type of train and track geometry.*

5 Elements of discomfort

5.1 On straight track

On straight track the theoretical movement of each object is described by a constant speed over time. It is obvious that no influence from track profile is introduced into the comfort evaluations.

However, because of the imperfections of the track alignment, married with the specific dynamic properties of the coaches of the train, an ensemble of random accelerations are transmitted to the human body and so some discomfort is introduced.

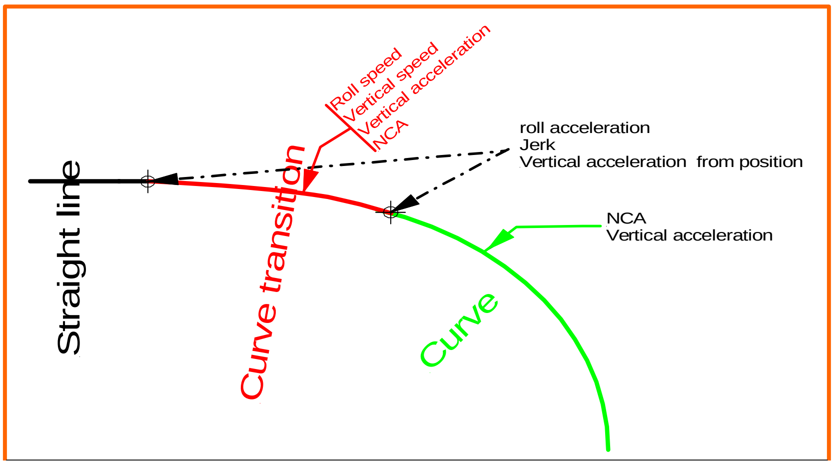
It is accepted that for a given track quality and a given coach the discomfort grows with speed, until a certain speed on which the dynamic response of the coach suddenly degrades.

5.2 On curved track

5.2.1 General definitions

Curved track consists of three main elements:

1. Straight track
2. Transition curves
3. Circular curves



Figur 5-1 *Different types of track element and their corresponding vibrational quantities.*

Straight lines are track sections with infinite horizontal curve radii.
Circular curves are track sections where the horizontal curve radii are constant and have finite values.
Transition curves are track sections where the horizontal curve radii change and *superelevation ramps* are track sections where the cant changes. Normally, these two sections are coincident.
Cant (*D*) (superelevation) is the height difference between the two rails (outer and inner rail in a curve), normally expressed in [mm] but can also be expressed as an angle (φ_t) [rad, °]. Cant is normally constant in circular curves.
Cant deficiency (*I*) is defined as the additional height (angle) the outer rail would have to be raised to achieve a quasi-static lateral acceleration in the car body (*RLA*) = 0. [mm, rad, °].

Each element may provoke a potential discomfort:

Circular curves add horizontal lateral acceleration due to centrifugal forces. This lateral acceleration is partly compensated by the cant of the track (see later). The remaining lateral acceleration at the track level is commonly described as the Non-Compensated lateral Acceleration (*NCA*). The cant of the track not only compensates for lateral acceleration but also introduces vertical supplementary weight as the vertical component of the centrifugal force. Tilting coaches are able to reduce the lateral acceleration percieved by the passenger further, so that only a fraction of the original acceleration remains. In this report, we will indicate this part as the remaining lateral acceleration (*RLA*) (i.e. the mean laterial acceleration perceived by the passengers).

Curve transitions add "roll speed" and "jerk" as commonly used parameters for describing discomfort. But there is also a vertical speed because of the changing angle of the coach. Moreover the remaining lateral acceleration and the vertical acceleration change from zero to their equilibrium values in the circular curves.

The intersection points of the curve transition with other elements add "roll acceleration" and "vertical acceleration" due to sudden changes in cant and possible tilting action.

Because of the importance of transition curves in relation to comfort, it is common to treat different situations separately because of their distinct influence on coaches and passengers.

The following types of transition curve can be distinguished, describing the phenomena by the angle of both bogies and the angle of the coach as input, together with a hypothetical behaviour of the coach as lateral acceleration in car body plane:

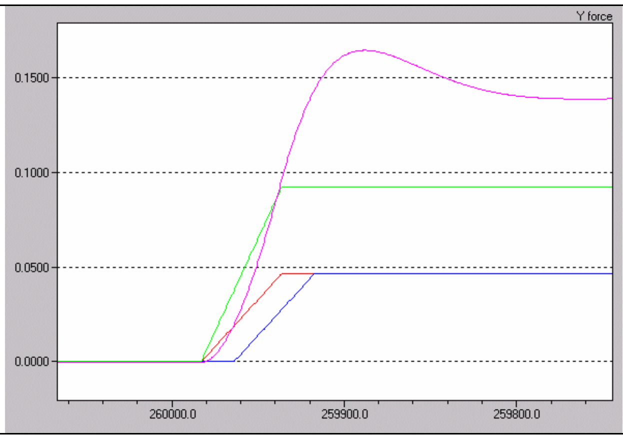
SIMPLE TRANSITION CURVE

Red: bogie 1 angle

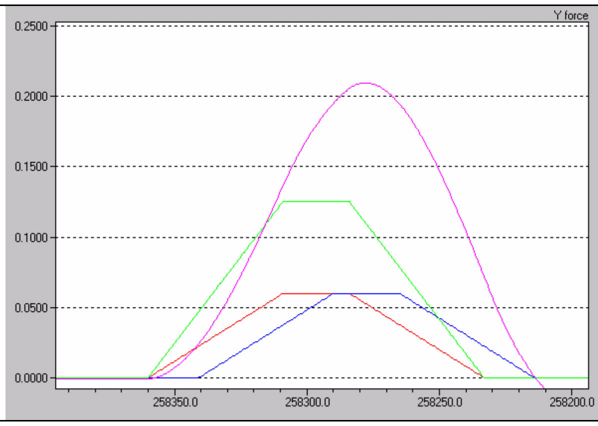
Blue: bogie 2 angle

Green: car body angle

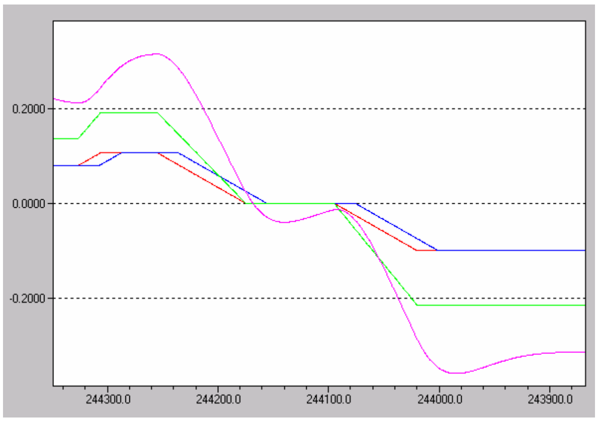
Fuchia: Lateral acc. in car body



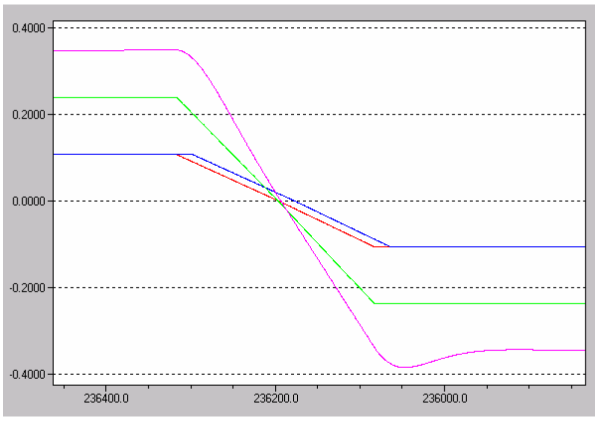
SHORT CURVE



ADJACENT CURVE
Two curves close to each other



REVERSE CURVE
Two curves with opposite direction in direct connection



COMPOUND CURVE
Curve with two or more circular curves

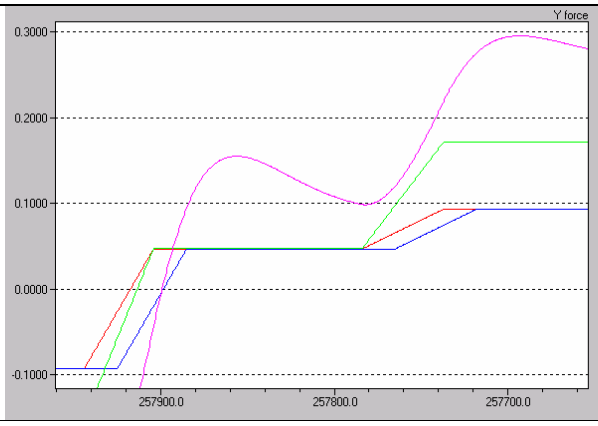


Figure 5-2 *Theoretical behaviour of lateral acceleration in a car and angles of both bogies and car in some different curves.*

5.2.2 Theoretical behaviour of those disturbing factors

5.2.2.1 The Non Compensated lateral Acceleration

Cause: The centrifugal force.

The general behaviour of *NCA* is described by the next figure.

The track angle, vertical acceleration and the vertical component of the centrifugal force behave in the same manner.

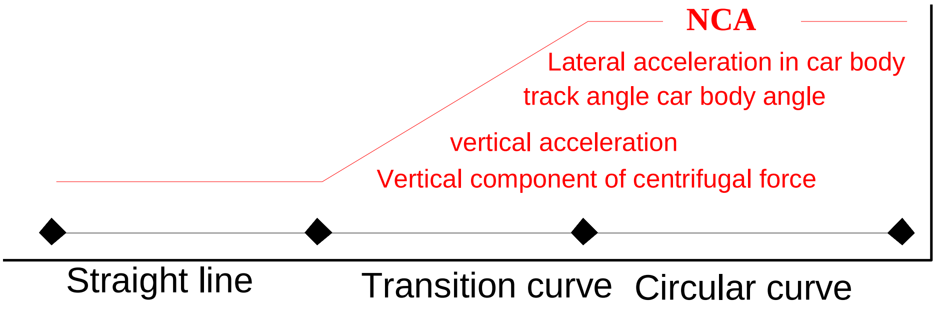


Figure 5-3 *Motion quanties that's approx. linearly with position in a transition curve.*

5.2.2.2 The roll velacity

Cause: changing of track angle.

The general behaviour is described by next figure.

The vertical speed due to the changing of track angle and car body angle behaves in the same manner.

The jerk (rate of change of lateral acceleration) also behaves in the same manner.

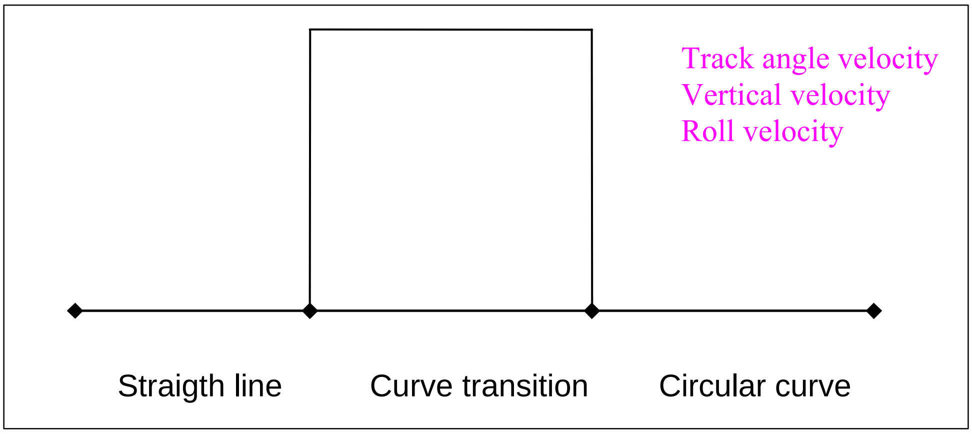


Figure 5-4 *Motion quantities that are approx. constant in a transition curve.*

5.2.2.3 Roll acceleration

Cause: change of track angle and car body angle velocity and vertical velocity.

It is clear that these phenomena need a more precise definition. Theoretically they are impulses.

This means that the time basis on which those phenomena are evaluated determines the amplitude.

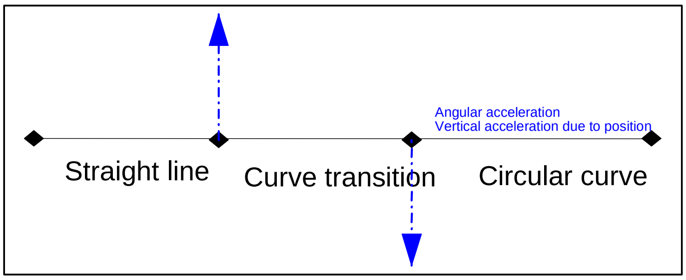


Figure 5-5 *Motion quantities that behaves as inputes at beginning and end of the transition curve.*

Curved track – repetition of events

The repetition of those events on a more or less regular basis during a journey can provoke supplementary discomfort.

5.2.3 Compensation of lateral acceleration discomfort in circular curves

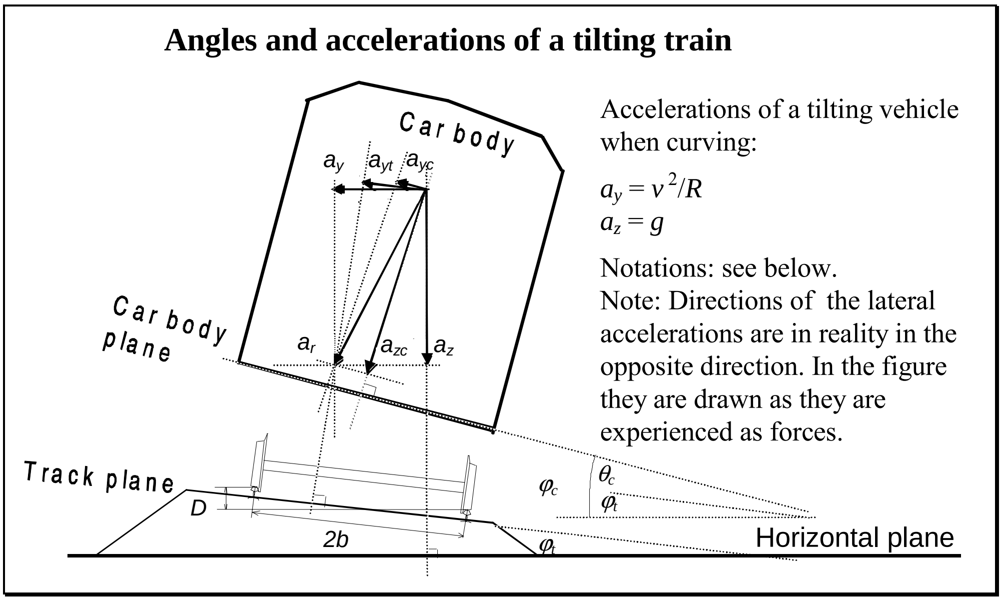


Figure 5-6 *Definition of angles and accelerations. Track cant is φ_t. Tilt angle of the coach body is θ_c. Total roll angle is $\varphi_c = \varphi_t + \theta_c$ to the horizontal plane. Vertical acceleration perpendicular to the horizontal plane is a_z,, lateral acceleration parallel to the horizontal plane is a_y and the resulting acceleration is a_r. Lateral acceleration in the coach body plane is a_{yc}.*

Nominal acceleration in the horizontal plane during curving

In a co-ordinate system (X_H , Y_H , Z_H) parallel and perpendicular to the horizontal plane the following nominal[1] accelerations during curving can be defined, see Figure 5-6:

$$a_{Y_H} = a_{yH} = \frac{v^2}{R} \qquad [\text{m/s}^2]$$

$$a_{Z_H} = a_{zH} = g \approx 9.81 \qquad [\text{m/s}^2]$$

where v is train speed [m/s] and R is curve radius [m].

Nominal acceleration in the track plane during curving

In a co-ordinate system (X_t , Y_t , Z_t) parallel and perpendicular to the track plane the following nominal accelerations (Non compensated acceleration *NCA*) during curving can be defined:

$$a_{Y_t} = a_{yt} = \frac{v^2}{R} \cdot \cos(\varphi_t) - g \cdot \sin(\varphi_t) \approx \frac{v^2}{R} - g \cdot \sin(\varphi_t) \qquad [\text{m/s}^2]$$

$$a_{Z_t} = a_{zt} = \frac{v^2}{R} \cdot \sin(\varphi_t) + g \cdot \cos(\varphi_t) \approx \frac{v^2}{R} \cdot \sin(\varphi_t) + g \qquad [\text{m/s}^2]$$

where cant angle is (φ_t) [rad], curve radius = R [m] and train speed v [m/s]

Perceived nominal lateral and vertical acceleration

In a co-ordinate system (X_c , Y_c , Z_c) parallel and perpendicular to the coach body (coach body floor) plane, the following nominal accelerations during curving can be defined:

$$a_{Y_c} = a_{yc} = \frac{v^2}{R} \cdot \cos(\theta_c + \varphi_t) - g \cdot \sin(\theta_c + \varphi_t) \qquad [\text{m/s}^2]$$

$$a_{Z_c} = a_{zc} = \frac{v^2}{R} \cdot \sin(\theta_c + \varphi_t) + g \cdot \cos(\theta_c + \varphi_t) \qquad [\text{m/s}^2]$$

where cant angle is (φ_t) [rad], tilt angle (θ_c) [rad], curve radius = R [m] and train speed v [m/s].

Roll angle (φ) refers to the horizontal plane and *tilt angle* (θ) to the track plane.

For the roll angle of the coach body (φ_c):
$\varphi_c = \varphi_t + \theta_c$.

Effective roll factor (f_r), *roll coefficient* (s): $f_r = 1 + s = \frac{a_{yc}}{a_{yt}}$

$f_r > 1$ if the coach body rolls outwards during curving (conventional trains) and $f_r < 1$ for tilting trains.

[1] *Nominal* responses are the part of the acceleration that are caused by train speed, horizontal curve radius, cant and nominal tilt compensation. *Dynamic* responses are caused by all other inputs, e.g. track (and coach) irregularities, suspension characteristics, etc.

The *tilt compensation ratio* indicates how large proportion of the lateral acceleration in the track plane is reduced (compensated) and perceived by the passengers:

$k_c = 100 \cdot (1 - f_r)$, if $f_r < 1$. [%]

Note: There is a difference between theoretical tilt compensation in the tilt control system and the actual tilt compensation because of the roll-out in the suspension system.

Conclusion of this section

The lateral acceleration in the horizontal plane is the most important effect of the ride in curved track, both in amplitude and duration. The effect of that acceleration is balanced by the angular position of the track (cant) plus any extra tilting of the coach.

There is always an angle where the resulting lateral force perceived by the passenger is zero.

In conclusion, for a coach of zero length it is in theory possible to reduce the lateral acceleration to zero for each point of the track for a given speed, but the vertical acceleration and the roll angle will increase.

Therefore, in the curve transition the local radius and local cant angle of the track must follow some rules. In general, the angle of the track relative to the horizontal plane changes in a linear way from zero to the value used in the circular curve.

For a number of reasons full compensation is not wanted.

6 Actual evaluation rules

All the formulae below are extracted from the CEN European standard[2]. These formulae reflect the non-stationary motion environment of a railway journey, where passage of bridges, turnouts, curves etc. causes impacts, shocks, jolts, jerks, different levels of lateral acceleration, roll motions etc. Therefore, the models will be complex and need careful study in the relevant standards. Formulae are give here only as a first impression of what is needed to estimate comfort.

6.1 Evaluation of comfort on straight track

Complete formula (taking account of motions on the floor, on seat and on the backrest)

Equation 6-1

$$N_{VA} = 4\times\left(a^{w_b}_{ZP95}\right) + 2\times\sqrt{\left(a^{w_d}_{YA95}\right)^2 + \left(a^{w_b}_{ZA95}\right)^2} + 4\times\left(a^{w_c}_{XD95}\right)$$

Simplified formula (taking account only of motions on the floor)

Equation 6-2

$$N_{MV} = 6\times\sqrt{\left(a^{w_d}_{XP95}\right)^2 + \left(a^{w_d}_{YP95}\right)^2 + \left(a^{w_b}_{ZP95}\right)^2}$$

$a^{w_d}_{XP95}$	A_{XP95}^{Wd} is a weighted acceleration P indicates "floor position" and A indicates "seat interface" 95 means, a statistic must be used, take quantile of 95% w_d, w_b and w_c are different weighting functions Note: weighting functions are optimised for for straight track because of a cut-off frequency of 0.5 Hz. Therefore steady state situations during curving are not taken into account.

6.2 Evaluation of comfort on curved track

6.2.1 Comfort at curve transitions

The CEN standard only gives a non-obligatory estimation of local discomfort. Also this method is complicated and needs careful study in the standard.

Equation 6-3

$$P_{CT} = (A.\ddot{y} + B.\dddot{y} - C) + D.v^{E}$$

Where

Table 6-1 *Coefficients for evaluation of P_{CT}.*

Condition	A	B	C	D	E
In rest – standing	2.80	2.03	11.1	0.185	2.283
In rest – seated	0.88	0.95	5.9	0.120	1.626

[2] CEN ENV 12299: Railway applications, Ride comfort for passengers, Measurement and evaluation.

P_{CT} = comfort index related to Curve Transition evaluation.

$\ddot{y}$ = maximum value of lateral acceleration in the coach body averaged on a 1 second base shifting by 0.1s, in the interval between the beginning of the entry or reverse transition and the end +1.6 s , quantified in percent of g (gravitational acceleration = 9,81 m/s^2).

$\dddot{y}$ = maximum jerk, evaluated as maximum variation of two subsequent values of lateral acceleration 1 s apart, in the time interval between 1 s before the beginning of the entry or reverse transition and the end of the same, quantified in percent of g per second.

$\dot{\vartheta}$ = maximum absolute value of coach body roll velocity, $\dot{\varphi}_1$ averaged on 1 s base shifting by (1/10) s from the beginning to the end of the transition , quantified in degrees per second.

The formula is used for the transition entry on curves-and reverse transitions, having duration of at least 2 s.

6.2.2 Comfort at discrete events

Comfort at discrete events may be used on both straight tracks and circular curves.

Equation 6-4

$$P_{DE} \quad = a.\ddot{y}_p + b.\ddot{y}_m - c$$

Table 6-2 *Coefficients for evaluation of P_{CT}.*

Condition	A	B	C
In rest standing	1.63	2.65	37.0
In rest seated	0.83	1.28	21.7

P_{DE} = Comfort index related to Discrete Events Evaluation

$\ddot{y}_p$ = difference between the maximum value ($\ddot{y}_{max}$) and the minimum value($\ddot{y}_{min}$) measured within an interval of 2s on the signal $\ddot{y}$*, low-pass filtered according to Wd modified and digitised at least at 10 samples per second

$\ddot{y}_m$ = average value of the signal $\ddot{y}$ low-pass filtered in the same 2 sec interval

P_{DE} is calculated, with intervals of 2 s shifted by (1/10) s.

For each calculated value, the abscissa, in space or time, is given by the centre of the calculation interval.

6.3 Statistical interpretation of experimental results

6.3.1 General

In general, it is accepted that the experimental result (y) is a function of some measurements ($x,y,z\ldots$) and some random noise (ε) $\Rightarrow$ $y = f(x,y,z \ldots) + \varepsilon$.

Statistics allows us to estimate the coefficients in that relationship only if we know the form of a relation.

A selected choice of parameters is at our disposal for the qualification of the result of the estimation procedure, all of them based on the variance of numbers.

Important variances

S_0 = var(y)	Variance without regression applied
Sr = var(ε)	Remaining variance, after applying regression
S_{expl} =var(y)-var(ε)	Explained variance

Important qualifying parameters

FISCHER-SNEDECOR	
$F_{\alpha/2,p-1,N-p} := S_{expl}/S_0*(N-p)/(p-1)$ N= number of observations p number of parameters in regression	if $F > F_{lim}$ then the hypothesis that not all coefficients in f(x,y,z,..) are zero can be accepted
CORRELATION	
ρ=sqrt(S_{expl}/S_0)	ρ =1 means a perfect relation ρ=0 means no relation at all
$prob(\rho = 0) \Rightarrow t_{\alpha/2,n-2} = \frac{\rho}{\sqrt{1-\rho^2}} \times \sqrt{n-2}$	The probability of ρ=0 must be judged by a associated "*t*" parameter and this depends on the number of observations.
STUDENT	
$t_{\alpha/2,n-p}$= Variance/average	if $t > t_{lim}$ then the hypothesis that the parameters is zero is rejected

Parameter of Fischer-Snedecor

This parameter allows us to test the hypothesis that all regression coefficients are zero against the proposed relation.

The correlation

On its own this parameter is only an indication. Indeed it is sufficient to have an important number of coefficients in the regression to let this parameter grow to one. Its significance has to be judged by a "student–test", as indicated above.

In the case of a very low correlation but an large number of observations, the correlation can be significant. This is the case in the average comfort investigation (See below).

The *t* parameter

The t parameter judges each individual coefficient in the regression. In principle each parameter in the regression with a low t-value should be removed.

This operation lowers the overall correlation, but the remaining coefficients receive a higher t factor.

6.3.2 Application in the case of comfort investigation

It is well documented that the scatter of the comfort judgement is very high, both for the individual variance and for the inter-individual variance. This means var(y) is large.

The only method to deal with this variance is to use a very high number of test persons and/or a very high number of observations. This is because the variance is not caused by some known measurable influences.

Budget constraints seriously limit the possibility of these solutions. In spite of these constraints, meaning that we will have to deal with a significant remaining variance, it is possible to find a regression with coefficients statistically different from zero.

This is the case in the average comfort regression.

As an example, consider the following possible (not necessarily optimal) regression for average comfort:

Table 6-3 *Example of a regression statistics for an average comfort model.*

F	6,942121	3	220	prob(F=0)= 0.000174
Var_0	119.5264			
Var_{rem}	109.1899			
Corr	0.294073	t=4.5428		Prob(t=0)=9.19E-06
	param	**Var**	***t***	**Prob (t = 0)**
H1	0.038025	0.059314	0.641087	0.522124
Y3	0.510903	0.123726	4.129316	5.14E-05
YM	0.287664	0.221458	1.298956	0.195301
NAVP_3	0.193144	0.092694	2.083668	0.03833

The probability that F=0 for 3 and 220 degrees of freedom = 0.002%.

7 Choice of the test zone

7.1 Choice of the test route

Initially, the working group asked four different countries to propose a test route that would be suitable for the assessment of passenger comfort on curved track.

The proposed requirements for the test were for a route which should be about 40 minutes long, with at least 15 curves. If possible the train should be able to run at higher than normal cant deficiency (to give up to a non-compensated lateral acceleration of up to $1.5m/s^2$ non-tilting, and at least $2.0m/s^2$ tilting).

Eventually, four different test routes were proposed – with three different types of tilting train.

- Italy: Firenze to Arezzo, 83km, FIAT ETR470
- Germany: Karthaus to Merzig, 43km, train –ADtranz VT612
- Sweden: Järna – Linköping, 180km, ADtranz Bm73
- Norway: Kongsberg to Nelaug, 182km, ADtranz Bm73

7.1.1 Evaluation of the offered routes

The first phase of the working group's study was a detailed evaluation of the test offers from the four countries, considering the range of conditions that could be achieved with the combination of test route and test train.

The evaluation was undertaken with the aid of simulations using the Vampire® rail vehicle dynamics software from AEA Technology Rail. This evaluation was reported in detail in AEA Technology Report AEATR-T&S-2000-108.

For each of the proposed routes offered by the four countries, the track geometry was supplied to the working group in the form of a spreadsheet giving curvature and cant values and the start and end points of transitions and curves. This information was converted into a Vampire® track geometry input file for each route.

Speed information was also supplied for the routes. This was converted into speed profiles by use of realistic acceleration and braking curves.

Vehicle information was also requested from each country, to enable a Vampire® vehicle model to be built of a tilting train for each route. In the case of the ETR470 train, a complete Vampire® vehicle model was supplied by FIAT, with the tilting control system modelled in an executable subroutine. In the case of the VT612 train, ADtranz Germany were not willing to supply sufficiently detailed parameters to allow a mathematical model to be developed, so a "typical" tilting train model had to built using the correct train length, bogie spacing and wheelbase. Suspension parameters and the tilt control algorithm were based on the former British APT train.

Simulations were undertaken for all four countries of a tilting train running at standard tilting speeds. Two countries were selected for more detailed analysis with a number of alternative speed profiles being investigated with both tilting and non-tilting conditions.

The results were evaluated on two criteria. Firstly, the types and distribution of the curves were examined, to see how practical it would be to undertake the tests. Secondly, a selection of curve transitions was analysed by calculating the key parameters relevant to comfort – lateral acceleration, lateral jerk, roll velocity and roll acceleration. The range and spread of these parameters was then compared for each route. Ideally, the widest possible spread of each parameter, and the lowest possible correlation between them, would give the best conditions for the testing.

The German test route was found to differ from other routes, in that all of the reverse curves had a section of straight between the adjacent exit and entry transitions. This was different from the test routes in other countries. Furthermore, the lack of parameter details for the tilting train would not allow any further work to validate the simulations against eventual test results.

The Norwegian test rote was also found to be unrepresentative, in that the route comprised an almost continuous series of reverse curves with very few simple entry transitions.

The Swedish and Italian test routes both offered a good selection of different simple and reverse curves. The Swedish test route gave less correlation between the different parameters in the transitions, which would have given the best spread of input conditions. However, it was concluded that the Italian route would be a suitable alternative provided that different tilt compensation levels could be achieved in the train.

Eventually, for practical reasons of availability of the test train, the Italian test route was chosen.

7.2 Selection of Test Zones

For the local comfort tests, it was necessary to select in advance the curve transitions and the plain curve sites to be used for the tests. In each case, the test subjects were to be alerted by an audible and visual signal to mark the start and end of the test zone.

The selection was based on the results of a further Vampire® simulation of the tilting train in the test zone. This represented the test train running at its maximum test speed (which gave up to 2.0m/s non-compensated acceleration, compared to the 1.8m/s normally used in commercial service in Italy).

Plots were prepared of the predicted train speed, bogie lateral acceleration, and tilting body lateral acceleration, jerk and roll velocity. These plots were used to select the test zones.

For simple **entry transitions**, the following criteria were used to identify suitable cases.

- At least five seconds of straight track before the start of the transition
- At least three seconds of steady curve after the end of the transition
- The train not to be accelerating or braking through the test zone

On this basis, 38 candidate transitions were identified in the Firenze–Arezzo direction. To maintain an acceptable burden of work for the test subjects, and in the subsequent analysis, a subset of 15 of these were chosen as test zones. To make this selection, a scatter plot was produced of the roll velocity against non-compensated acceleration (Figure 7-1).

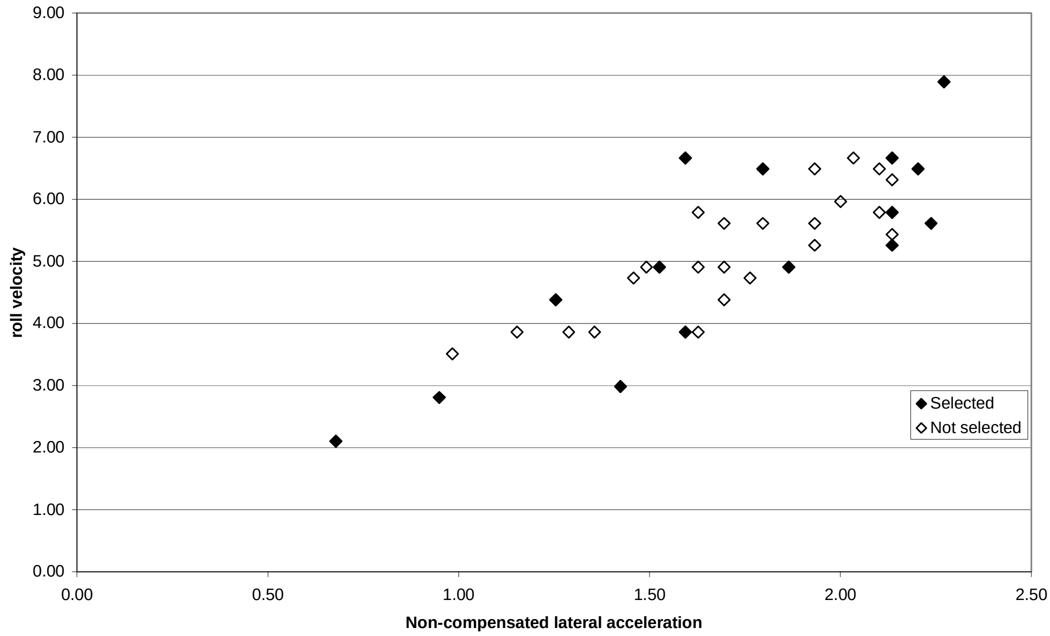


Figure 7-1 Lateral acceleration versus roll veclocity for Firenze–Arezzo entry transitions.

Sites were selected to maximise the spread of the data in terms of both lateral acceleration and roll velocity, while maintaining sufficient separation between test zones. A time history plot of the non-compensated acceleration on the test route is shown in Figure 7-2 with the selected entry transitions shown by the letter “T”.

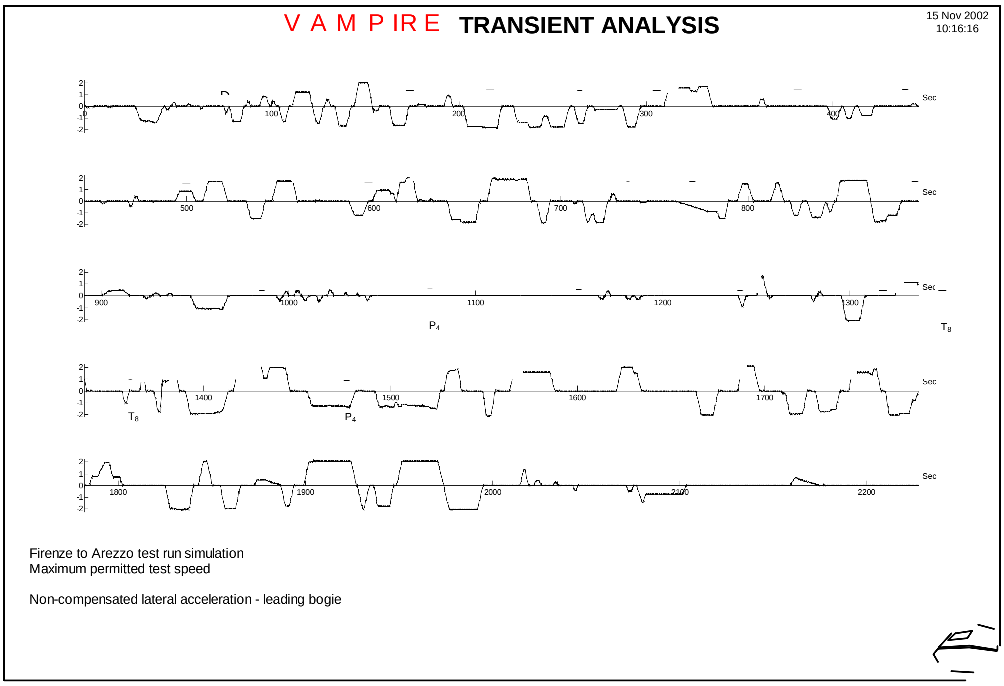


Figure 7-2 Selection of test sections. Firenze to Arezzo.

A smaller selection of other types of transition were also chosen as follows…

- **Reverse transitions** – four reverse transitions were selected, where the exit transition of a first curve immediately joins the entry transition of the next curve of the opposite hand. These are shown by the letter “R” in Figure 7-2.
- **Adjacent transitions** – four adjacent transitions were selected, where the exit transition of a first curve is separated from the entry transition of the next curve by a short length of straight track. These are shown by the letter “A” in Figure 7-2.
- **Compound transitions** – three compound transitions were chosen, where a curve of modest radius changes to a curve of tighter radius of the same hand. These are shown by the letter “C” in Figure 7-2.
- **Short curve** – one test zone was chosen to include a short transition onto a very short curve. This is shown by the letter “S” in Figure 7-2.

In addition, nine **plain curve** sites were selected, for the separate analysis of comfort on plain curves. The main criteria were to find a selection of curves with a sufficient length of constant radius, with a range of non-compensated accelerations. Two of the “plain curve” sites had infinite radius (i.e. straight track). Plain curve zones are shown with the letter “P” in Figure 7-2.

Finally, four “**dummy**” zones were chosen (all on straight track). These had two purposes. The first was to fill-in long gaps between chosen test zones to keep the test subjects alert. The second purpose was to minimise the possible effect of forewarning of the test subjects on their judgement of entry transitions, by ensuring that less than half of the test zones were entry transitions. In the dummy zones the votes were recorded, but no vehicle acceleration data was analysed. The dummy test zones are shown in Figure 7-2 by the letter “D”.

Throughout the selection process, a reasonably even spacing of the test zones was maintained to ensure that the process of voting could be completed well before the start of the next zone.

A similar process was used to select the test zones in the Arezzo–Firenze direction.

7.3 Quality of the track in the test zone

The quality level of the track in the chosen test zone is qualified as good.

This means that the track is suitable for higher speeds, as used by tilting trains.

The contrary condition would have given misleading results in the tests, because the level of vibrations would be higher than in normal commercial conditions.

As a result we can expect that the influence of vertical and lateral higher frequency vibrations is less that the corresponding influence in previous tests for vibratory comfort in the seated position.

8 Description of the test

8.1 The train

The comfort tests were undertaken on the ETR 470.0 tilting train belonging to Fiat Ferroviaria, now Alstom. This prototype of the ETR470 series, being for experimental use only, comprises only two power units (the intermediate BB2 and the BAC2 with cab and pantograph) and one trailer unit (RAC2, equipped with transformers, pantograph and cab).

The extreme coaches (RAC and BAC) are 2nd class, while the middle coach is a 1st class (BB).

The main characteristics are summarised in table 8-1.

The ETR 470 series is used for Cisalpino services; the tilt mechanism and the tilt condition are similar to those of the ETR 460 and ETR 480 series, belonging to Italian railways.

8.2 Main features of ETR 470.0

Table 8-1 *Main data for the three car train set ETR 470.0.*

ETR 470.0	BAC 2	BB 1	RAC 2	Total
Length [mm]	27 650	25 900	27 650	101 200
Bogie pivot [mm]:	1 900	1 900	1 900	
Bogie wheelbase [mm]:	270	270	270	
Diameter of new wheels [mm]:	890	890	890	
Roll flexibility coefficient in working order (*)	0.13	0.14	0.13	
Mass in working order [t]:	51	52	53	156
Traction motors:	3-phase asynchronous			
Drive system:	GTO Inverter			
Continuous power [kW]:	2000			
Power Supply:	3 kV D.C. and 15 kV 16 2/3 Hz A.C.			
Maximum operating speed [km/h]:	200			
Maximum Tilting-Angle [°]:	8			

8.3 Measured parameters

8.3.1 Measured signals

Since the train was running at higher than normal speed in curves, with non-compensated acceleration up to 2.0 m/s^2, all the signals requested by the UIC 518 leaflet were measured to verify the dynamic behaviour from a point of view of safety. The assessment of safety was good.

The measurements required for comfort aspects were carried out in each coach; the accelerometers for the vertical and lateral direction were on the floor of the car body, above each bogie and in the middle of the central coach, BB.

The longitudinal acceleration was measured in one position for each coach (above the extreme bogie in the BAC and RAC coach and in the middle of the BB coach), while the roll speed was measured in the middle of each coach.

The seats equipped with accelerometers placed in the interfaces, according to the CEN rule, were as close as possible to the median line of the coach.

Each of the five instrumented seats had a seat back interface measuring longitudinal acceleration, and a seat cushion interface measuring vertical and lateral accelerations.

Some general parameters such as vehicle speed and non-compensated acceleration on the bogie frame were also measured.

In the following table is a list of the measured parameters.

Table 8-2 *Measured parameters during the test runs.*

Symbol	**Measured parameters**
$\ddot{x}^*$	*longitudinal acceleration* on the floor of the car body
$\ddot{y}^*$	*lateral acceleration* on the floor of the car body
$\ddot{z}^*$	*vertical acceleratio*n on the floor of the car body
$\ddot{\mathbf{x}}_{\mathbf{D}}$	*longitudinal acceleration* on the seatback
$\ddot{\mathbf{y}}_{\mathbf{A}}$	*lateral acceleration* on the seat
$\ddot{z}_{\mathbf{A}}$	*vertical acceleratio*n on the seat
$\dot{\theta}^*$	*roll speed* on the floor of the car body
V	train speed
$\ddot{y}^+$ (*NCA*)	*lateral acceleration* on the bogie frame (non-compensated acceleration)
P1÷P32	signals of the 32 voting boxes

The distribution of measuring points (apart from the registration of votes) is summarised in figure 8-1.

8.3.2 Vote registration

32 test subjects participated in the tests to evaluate local and average comfort; for which each subject had a box with 5 push buttons. When an event occurred, a yellow lamp lighted on the box to indicate the beginning of the evaluation window and a green one for the end of the event (both lights are accompanied by a acoustic signal in the car body). At this point each subject had a few seconds (3–5) to express their evaluation by pushing the appropriate button on the box. Each button corresponded to one level of comfort:

1. very good
2. good
3. medium
4. poor
5. very poor

This graduation on 5 levels is quite similar to the comfort scale adopted in the ERRI B153 and then in the CEN rule.

8.3.3 Synchronisation between votes at different locations in the train

The theoretical positions along the track for the display of the yellow and green lights were carefully chosen, with the help of the simulated data (see chapter 7).

The voting lights went on in the whole test train at the same moment, at a time optimised for the centre of the middle coach. For the test train used, events have a time window that begins a little before and ends a little after so the problem here is not so important. If longer trains were to be used special measures would be necessary to improve synchronisation.

8.3.4 Synchronisation of the votes and the track sections to be judged

The train's track position was determined by specialised equipment, which was synchronised to the middle of the middle coach (except for the first 3 test zones).

8.4 Test conditions

8.4.1 Route

The tests were carried out on the conventional line from Firenze – Arezzo, in the week 15–19 October 2001.

The section from Firenze – Arezzo, belonging to the original line that links Firenze to Roma, is about 80 km long. The commercial tilting speed is allowed only on a part of the route, for historical reasons. The maximum speed is 180 km/h; it is characterised by curves with radius mainly from 350 to 600 m.

8.4.2 Test runs

The test programme was subdivided into two parts:

- test of local comfort;
- test of average comfort.

Each day at least two return journeys were carried out.

The test runs were undertaken at three levels of speed:

- *Vp* (commercial speed of tilting trains in Italy, up to 1.8 m/s^2 non-compensated acceleration, *NCA*).
- *Vmax* (up to *NCA* of 2.0 m/s^2).
- *Vnp* (non-tilting speed, up to *NCA* of 1.2 m/s^2. This is higher than the normal commercial speed for non-tilting trains in Italy with *NCA* of up to 1.0 m/s^2).

As the aim was to obtain the maximum spread of data, the level of tilt compensation was also changed. The percentage of tilt compensation before taking into account the roll-out in suspension was:

- 80% (the normal setting of the train)
- 60%
- 40%
- 0%, i.e. without tilting.

The following table shows the different test conditions for local comfort, depending on the test speed and tilting percentage.

Table 8-3 *Test conditions for local comfort and corresponding number of the test run.*

Tilting Percentage [%]	***NCA*** [m/s^2]	**Route Firenze – Arezzo** Test N°	**Route Arezzo – Firenze** Test N°
80	**2.0**	117	106
	1.8	103	
60	**2.0**	121	122
40	**2.0**	119	120
0	**1.2**	107	118

In a similar way, the following table summarises the test runs for average comfort, where the investigation did not include the compensation level of 40%.

Table 8-4 *Test condition for average comfort and the corresponding number of the test run.*

Tilting Percentage [%]	***NCA*** [m/s^2]	**Route Firenze–Arezzo** Test N°	**Route Arezzo–Firenze** Test N°
80	**2.0**	113	114
	1.8	115	116
60	**2.0**	109	110
0	**1.2**	111	112

The test runs with odd numbers are in the direction from Firenze to Arezzo and they have the RAC coach as leading vehicle; while the test runs with even numbers are in the opposite direction and the BAC coach is the leading vehicle.

8.4.3 Test subjects

The 32 test subjects were students from different local colleges, and were an equal mix of males and females. As far as possible the same individuals were used on each of the test days.

The test subjects were divided into 8 groups of 4 subjects; in the extreme coaches (RAC and BAC) there were two groups, while in the middle coach (BB) the other four groups were seated in three positions by dividing one group into two sub-groups. The exact position of the subjects is showed in Figure 8-2 (with the seats with interface accelerometers shown in yellow).

The groups were moved between tests with the aim of obtaining the vote from each group from each position in the test train (leading vehicle, middle vehicle etc.).

Recording of data was done in such a way that the relation between the recordings and the concerned group was maintained.

During the tests for local comfort, for each run of about 20 minutes the subjects had to vote for about 40 events, each of them very short.

On the contrary in the test run for global comfort, the subjects had to vote only 4 times; each test run was divided in sections of 5 minutes.

8.5 Registration of data, calculation of parameters

8.5.1 Method

All measured data were digitally registered in a continuous manner.

The working group chose a number of parameters, believed to be important for the evaluation of comfort. The working group defined the kind of parameter and the method needed for the calculation.

The test organisation calculated the parameters from the registered data, and handed the results over to AEA Technology, who were responsible for the multiple regression analysis.

8.5.2 Comment

This method of work could be time consuming if it becomes evident later that the preliminary choice of parameters by the working group was not optimal, then the whole procedure has to start again. It is definitely better for the organisations charged with the analysis of the data, to work with the database of recorded data, and to select the data by computer program.

8.6 Measurements for comfort

8.6.1 Location and type of sensors

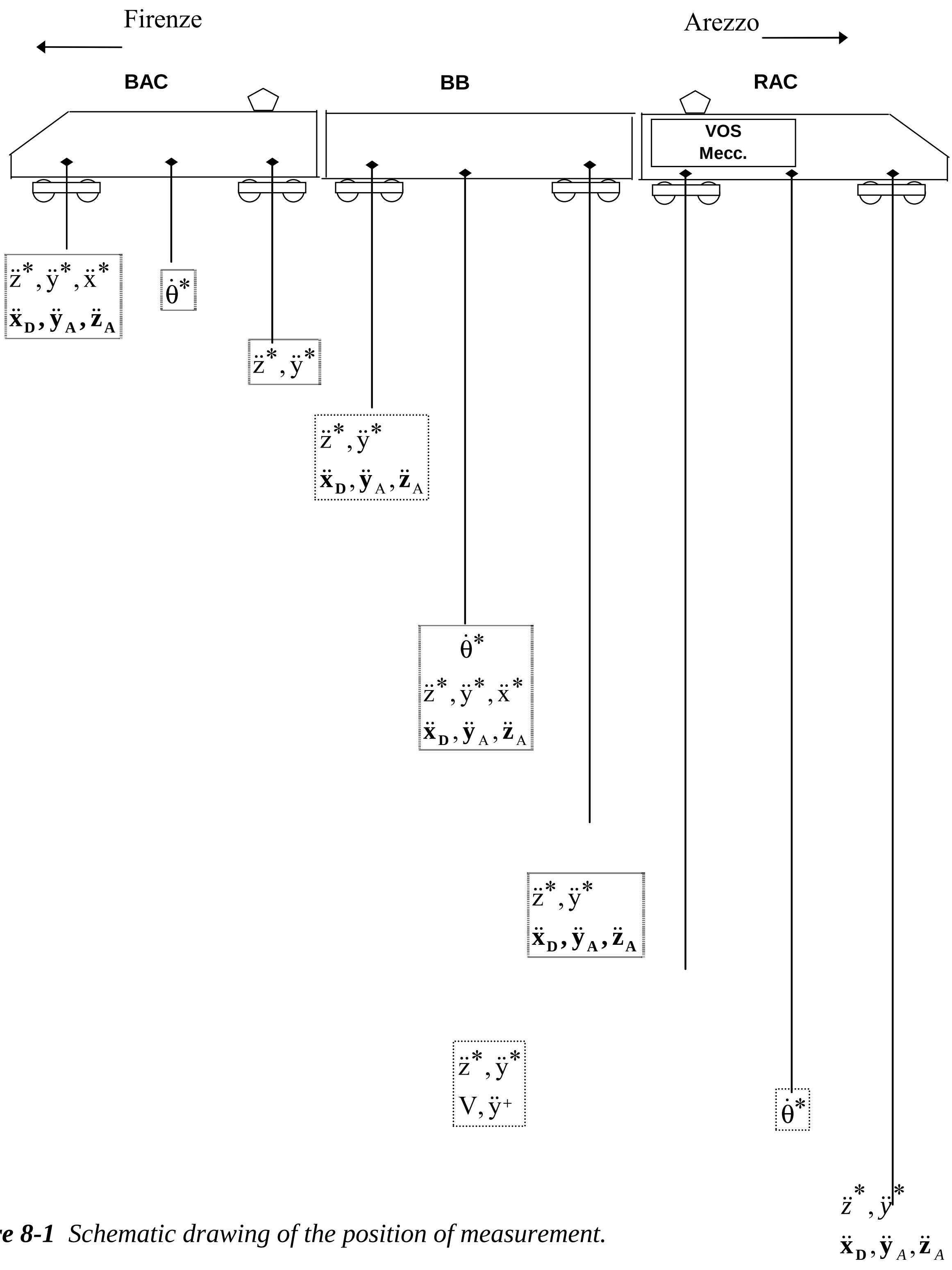


Figure 8-1 *Schematic drawing of the position of measurement.*

8.6.2 Occupied places

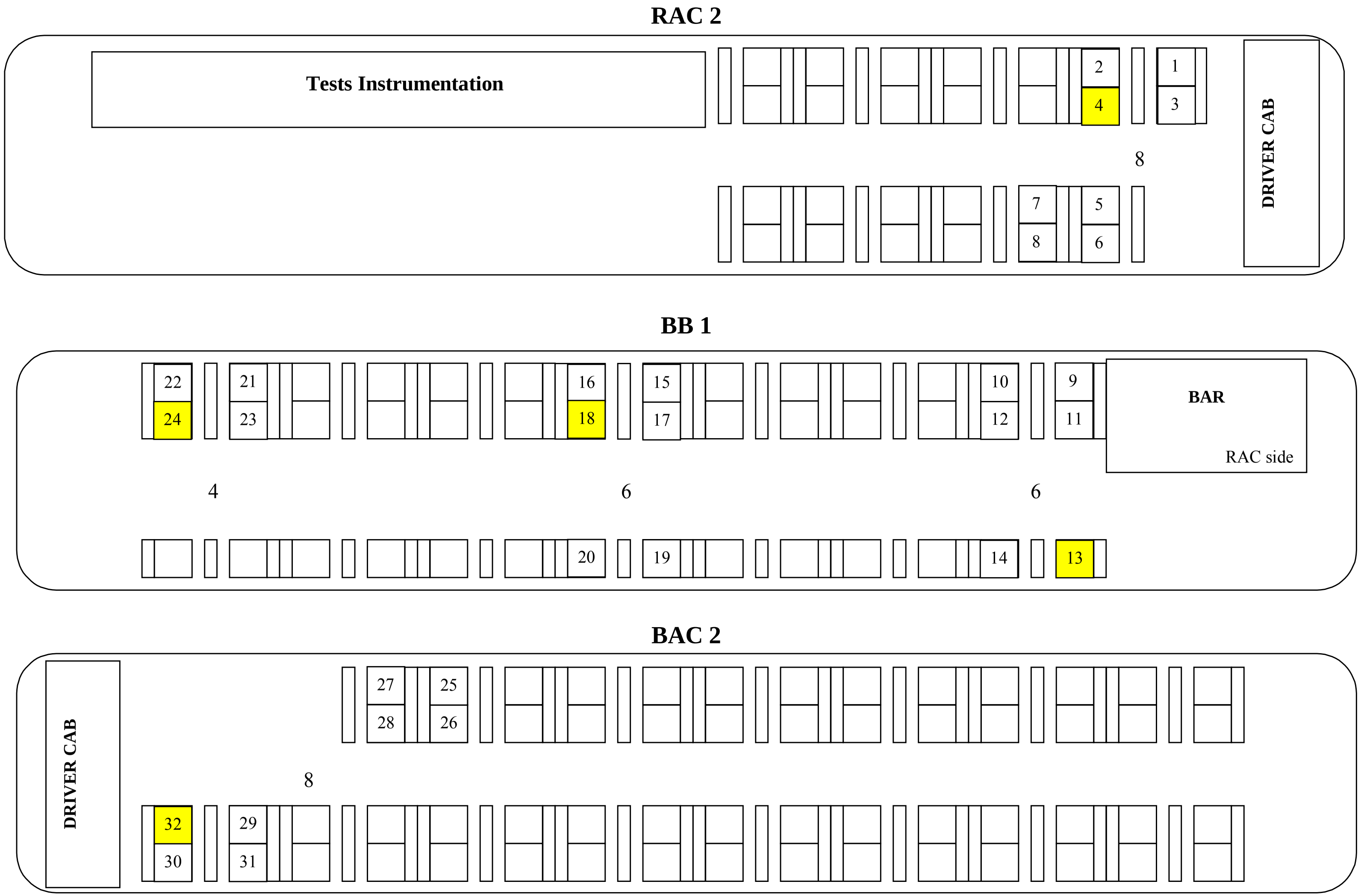


Figure 8-2

9 Possible influences of construction concepts of vehicle, track and/or system functioning on comfort

9.1 Introduction

Compensation for lateral acceleration is possible in circular curves by tilting the car body. In transition curves however, ideal compensation is only possible for one perpendicular plane in the coach. Factors that affect the compensation will be explained in this chapter by examples, indicating influences on the angular position of the coach and/or the influence on the remaining lateral acceleration.

- The length of the coach causes a less ideal angular position of the coach on the track and so introduces a difference between theoretical and real angular position. Compensation by software is in principle possible
- A position in the coach away from the ideal perpendicular plane of compensation causes higher lateral acceleration
- A time delay in the tilting system also causes higher lateral acceleration
- Constraints on maximum tilt angle or tilt rate may also give higher lateral acceleration
- The influence of dynamic reactions of the coach on the imposed angular positions shortens the time of full compensation, and so augments periods with more then necessary lateral acceleration.

9.2 Basis for the examples in this chapter

The examples are based on a simplified simulation, with the following assumptions:

Radius: 600 m
Cant: 140 m
Length of transition curve: 70m
Maximum tilt angle: 8°
Equilibrium speed at max tilt: 134.511 kph
Tilt limitation: variable (100% and 80%) of max tilt used
Compensation level variable: (100% and 80% used)
Length of vehicle: 19 m
Place in vehicle: variable
Time delay: (0 sec and 0.5 sec used)

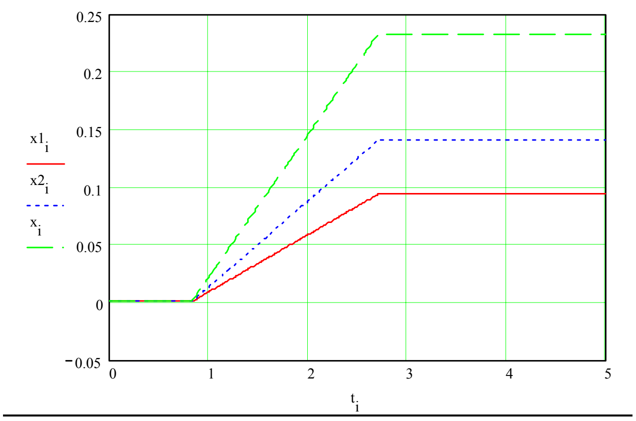
9.3 Study of the car body angle

9.3.1 Influence of vehicle length

The total roll angle is the sum of two angles;

the angle of the track (average angle of first and last bogie)

the tilt angle of the car body



Principle

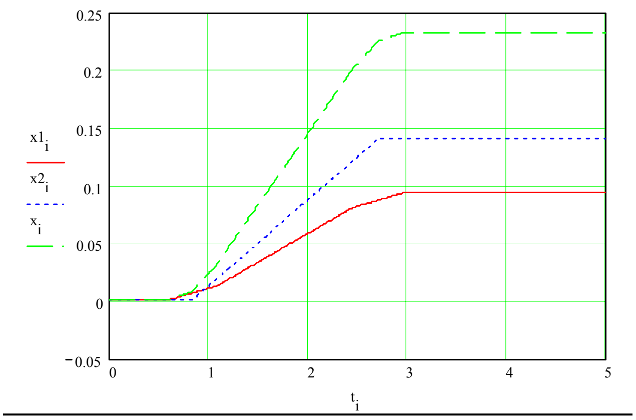
Blue dotted line: angle due to car body tilt (x_2)

Red solid line: angle due to track (x_1)

Green dashed line: roll angle (x)

The roll angle is the sum of the angle due to cant and tilt

Figure 9-1 *Roll and tilt angles due to the position: transition curve.*



The red solid line, representing the induced angle from the track has more then one slope (x_1)

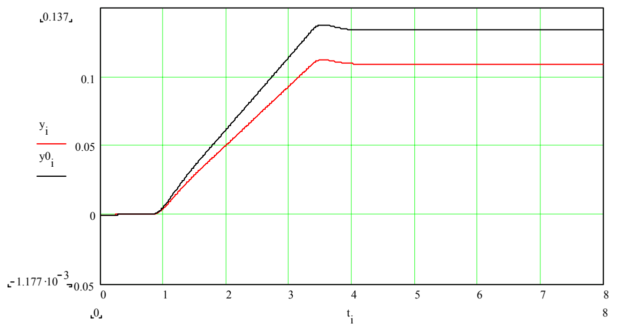
The blue dot line, representing the car body tilting has same properties as before. (x_2)

Green dashed line: roll angle (x)

At the beginning and the end of the transition, the vehicle receives its roll angle more smoothly. In the middle of the transition, only the central part of the coach has a correct roll angle.

Figure 9-2 *Different angles due to position and vehicle length.*

9.3.2 Influence of the flexibility of the suspension



This picture gives the car body angle. (y_i)

The red (bottom) line gives the car body angle taking account of flexibility of 19% a roll out of the supension.. (y_I)

The centrifugal force reduces the imposed car body angle.

Figure 9-3 *Car body angles with and without supension flexibility.*

However, the dynamic reaction also means that the equilibrium position is reached somewhat later. This error cannot be avoided and has an influence on track containing a lot of short curves and transitions. The picture below gives an extract from the real test track, containing a succession of curves.

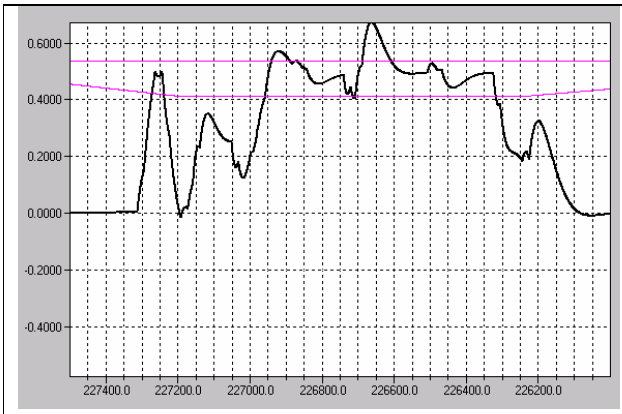
The showed angles (red, blue and green) contains a number of horizontal parts representing the circular curves.

The fuchsia line gives the calculated roll angle, where most of the horizontal parts have disappeared because of the dynamic reaction of the vehicle.

Figure 9-4 *Calculated track, bogie and roll angles for track and car body in a combinded curve showing the dynamic reaction of the flexibility of the suspension.*

9.4 Influence on lateral forces

9.4.1 Influence of the dynamic behaviour



The dynamic reaction causes lateral accelerations which are greater on some occasions then the planned 0.5 m/s^2

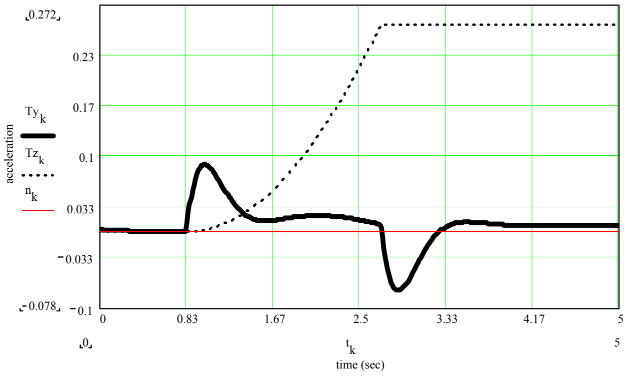
Figure 9-5 *Lateral acceleration in the car body.*

9.4.2 Influence of length of the coach

The lateral and vertical accelerations are shown in the figures below.

Theoretical behaviour
Resulting lateral acceleration with full (100%) compensation

The bumps at the beginning and the end of the transition are provoked by the dynamic response of the coach to the sudden changes in accelerations. The amplitudes are small - max 0.1 m/s^2.



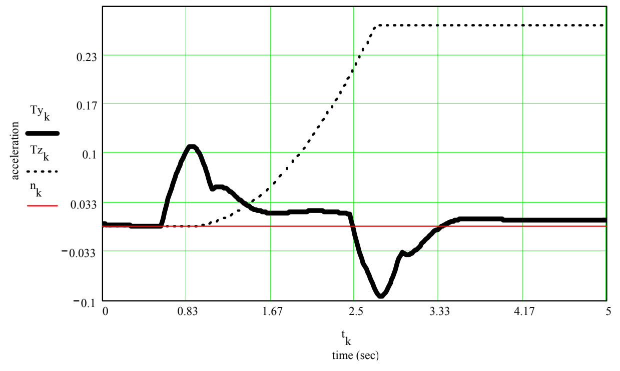
Thick curve: represents the car body acceleration
Dotted curve: represents the vertical acceleration induced by centrifugal force
– max about 0.25 m/s^2

Ty_k: resulting lateral acceleration
Tz_k: resulting vertical acceleration

Figure 9-6 Behaviour of lateral and vertical acceleration in a train with 100% tilt compensation.

Vehicle length of 19m, full compensation
(Simplified calculation)

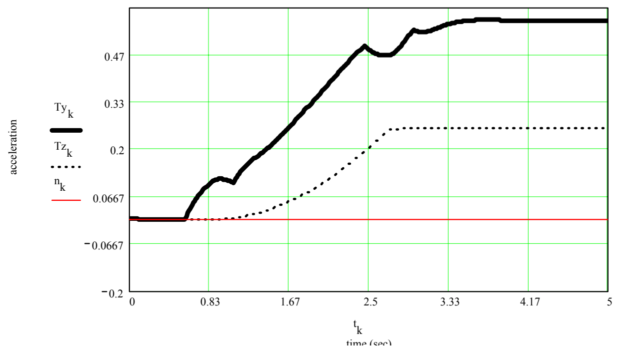
There are contradictory influences. First, the sudden changes at the beginning and the ending of the curve transition are spread out. Secondly the angular position of the vehicle is less accurate.



Ty_k: resulting lateral acceleration
Tz_k: resulting vertical acceleration

Figure 9-7 Behaviour of lateral and vertical acceleration with 100% tilt compensation taking account of the vehicle length.

Situation with 80% compensation of lateral acceleration.



$\max(Ty) = 0.563\,\text{m}\cdot\text{sec}^{-2}$

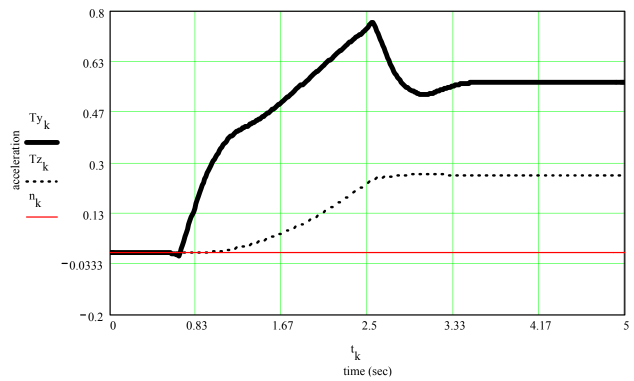
$\max(Tz) = 0.258\,\text{m}\cdot\text{sec}^{-2}$

Figure 9-8 *Behaviour of the lateral and vertical acceleration with 80% compensation and the vehicle length.*

9.4.3 Influence of position in coach

Position on first bogie

The momentary lateral acceleration is greater then the target for some time.



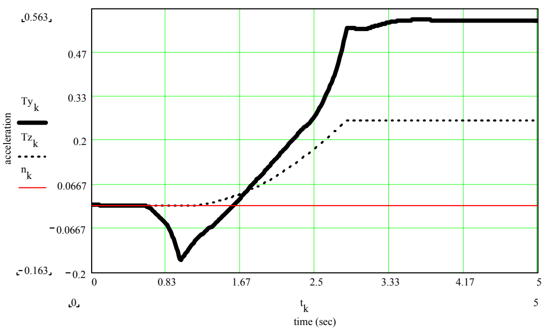
$\max(Ty) = 0.77\,\text{m}\cdot\text{sec}^{-2}$

$\max(Tz) = 0.258\,\text{m}\cdot\text{sec}^{-2}$

Figure 9-9 *Behaviour of lateral and vertical acceleration over the first bogie.*

Position on last bogie

The sign of the lateral acceleration changes in the beginning of the transient curve, but is never higher than the target.



$\max(Ty) = 0.563\,\text{m}\cdot\text{sec}^{-2}$

$\max(Tz) = 0.258\,\text{m}\cdot\text{sec}^{-2}$

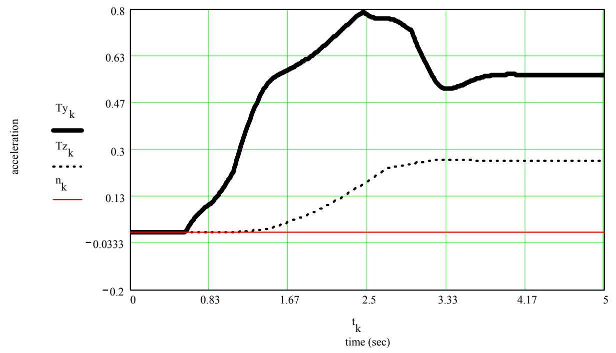
Figure 9-10 *Behaviour of lateral and vertical over the last bogie.*

9.4.4 Additional discomfort due to functioning servo mechanisms

Influence of time delay 0.5 sec

Position: in the middle of the coach

The influence closely resembles the situation on the first bogie with no time delay.

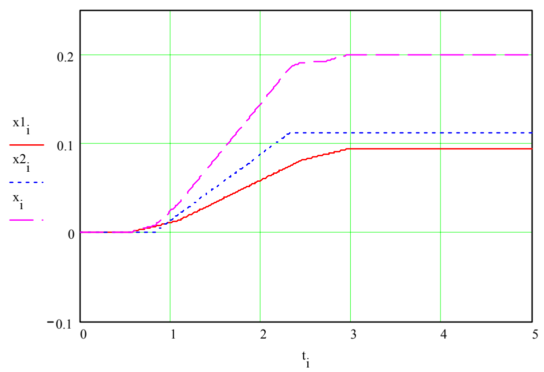


$\max(Ty) = 0.788\,m\cdot sec^{-2}$

$\max(Tz) = 0.259\,m\cdot sec^{-2}$

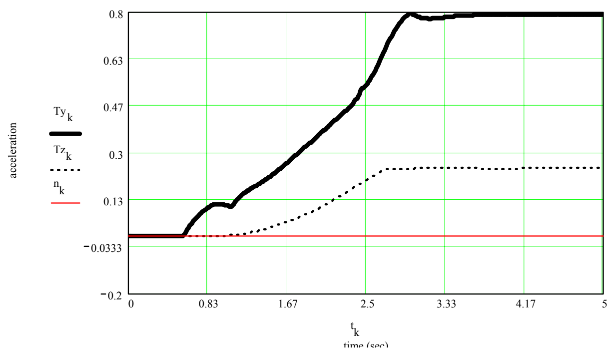
Figure 9-11 *Behaviour of lateral and vertical acceleration when there is a time delay of 0.55.*

Influence of reaching maximum tilt



The tilt angle of the car body stops too soon

Figure 9-12 *Limitation of tilt angle.*



Position in the middle of the coach

$\max(Ty) = 0.795\,m\cdot sec^{-2}$

$\max(Tz) = 0.243\,m\cdot sec^{-2}$

The influence is mild, the target value becomes higher, but there is no overshoot.

Figure 9-13 *Behaviour of lateral and vertical acceleration when the tilt angle is limited.*

10 General evaluation of local comfort results

10.1 Evaluation of votes

The 32 test subjects were divided into eight groups (A, B, C, .., H). The eight groups shifted position in the train during the stops in Firenze. There were seven different positions in the train, which means that one group of four was divided into two subgroups of two and joined another groups during the test runs.

The recordings of votes were from these seven positions. Before further analysis, the individual votes from these seven positions were averaged to a mean vote for the position in question. The distribution of these mean votes is not normal, but can be regarded as approximately normal, see Figure 10-1 and Figure 10-2 for the both directions of travel. Table 10-1 shows the difference in mean values in votes for the two directions.

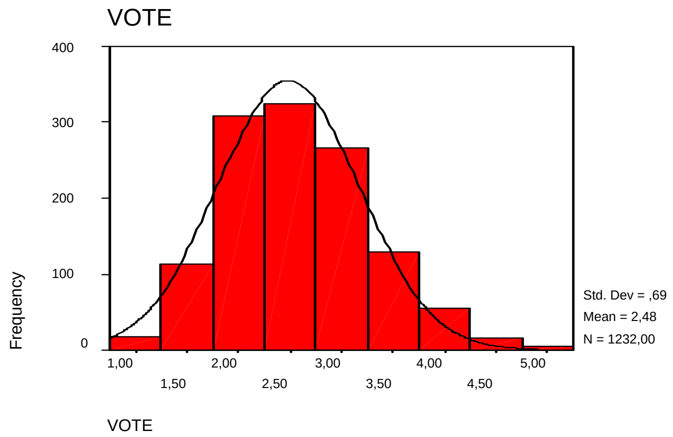


Figure 10-1 *Distribution for votes on Firenze–Arezzo test runs.*

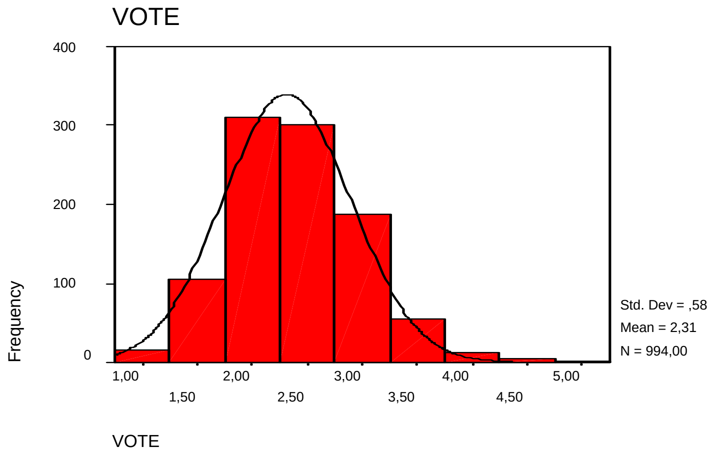


Figure 10-2 *Distribution for votes on Arezzo–Firenze test runs.*

Table 10-1 *Average comfort vote for each group for the different test run directions.*

VOTE	Direction	N	Mean	Std. Deviation	Std. Error Mean
	Firenze–Arezzo	1 232	2.483	.691	.0197
	Arezzo–Firenze	994	2.312	.583	.0185

10.1.1 Conclusions

The actual distribution is close to a normal distribution in the central parts, meaning that out of average conditions are rare; otherwise one would expect a distribution with a wider shape.This is an unfortunate condition for test evaluation. Most of the points are central points.

The difference between the mean values can be associated with a t value = 6.33 with 2221 degrees of freedom. As a conclusion, the difference is small but significant.

10.1.2 Remark

Note, this difference may be explicable by the differences in the conditions of ride. The calculation only suggests

- The voting in the two conditions is different, so it may be possible to find an evaluation formula.
- The difference in voting is small, so finding a regression can be tough.

10.2 Variation between groups

Table 10-2 *Difference in voting between different groups.*

Group	Direction	Mean	N	Std. Deviation
A	Arezzo–Firenze	2.380.	142	0.505
	Firenze–Arezzo	2.415	176	0.631
	Total	2.399	318	0.578
B	Arezzo–Firenze	2.653	107	0.705
	Firenze–Arezzo	2.470	141	0.559
	Total	2.549	248	0.631
C	Arezzo–Firenze	2.227	107	0.552
	Firenze–Arezzo	2.682	106	0.724
	Total	2.453	213	0.681
D	Arezzo–Firenze	1.939	106	0.488
	Firenze–Arezzo	2.420	141	0.735
	Total	2.214	247	0.683
E	Arezzo–Firenze	2.451	142	0.617
	Firenze–Arezzo	2.264	176	0.655
	Total	2.347	318	0.644
F	Arezzo–Firenze	2.237	142	0.486
	Firenze–Arezzo	2.267	176	0.616
	Total	2.253	318	0.561
G	Arezzo–Firenze	2.353	142	0.515
	Firenze–Arezzo	2.838	140	0.735
	Total	2.594	282	0.678
H	Arezzo–Firenze	2.200	106	0.565
	Firenze–Arezzo	2.648	176	0.687
	Total	2.480	282	0.678
Total	Arezzo–Firenze	2.312	994	0.583
	Firenze–Arezzo	2.483	1232	0.691
	Total	2.407	2226	0.651

There exist some differences between the average votes from the different groups (A–H) and also between the directions of the test run. It is possible to follow the shifting of the groups but not each individual. It could be misleading to conclude that one group voted on average higher than another group because a single group could be placed in a position in the train with higher (dis)comfort values during runs with higher average discomfort. Nevertheless, it can be interesting to show the difference between the groups, and if there are any significant differences in the average voting between the groups (Table 10-2).

10.2.1 Significance of the difference

Table 10-3 shows a t-test to check whether the difference of voting between group A and group G is significant for the test runs in the direction of Firenze–Arrezo.

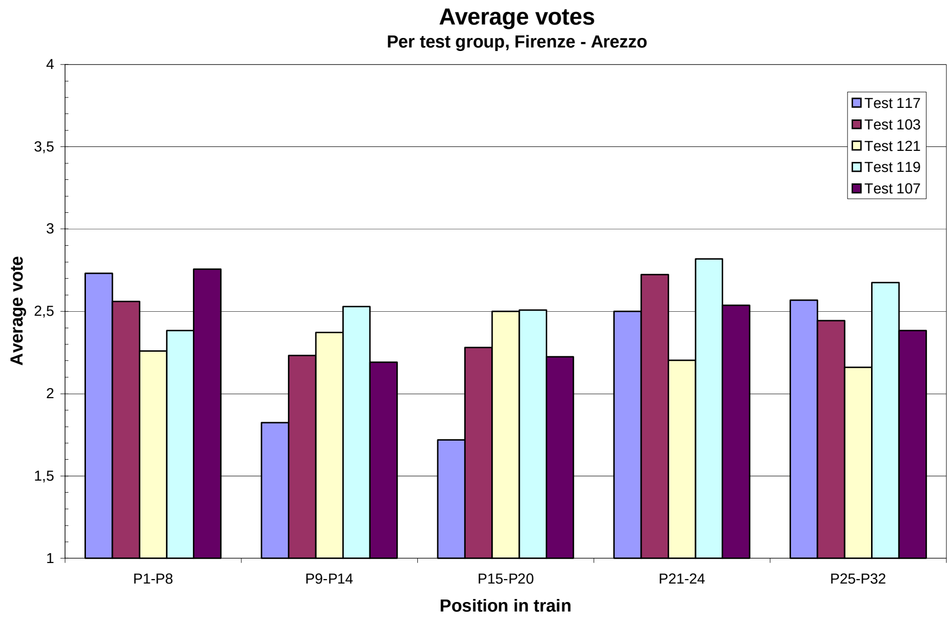
Table 10-3 *Independent Samples Test between Group A and G, Firenze–Arezzo.*

		Levene's Test for Equality of Variances		**t-test for Equality of Means**					**95% Confidence Interval of the Difference**	
		F	Sig.	*t*	*df*	Sig. (2-tailed)	Mean Diff.	Std. Error Diff.	Lower	Upper
VOTE	Equal variances assumed:	4.013	.046	-5.499	314	.000	-.423	.0769	-.574	-.272
	Equal variances not assumed:			-5.405	274.6	.000	-.423	.0782	-.577	-.269

The test shows that there is a significant difference between the voting in groups A and G. This condition can be the consequence of different vibration stress input. It is still the intention that a proper regression will take these differences into account, so that after regression the influence of position in the train is no longer significant.

10.3 Seat position

The influence of the seat position on the mean vote is shown in Figure 10-3. There is no difference evident between the different positions in the train except for test run 117.



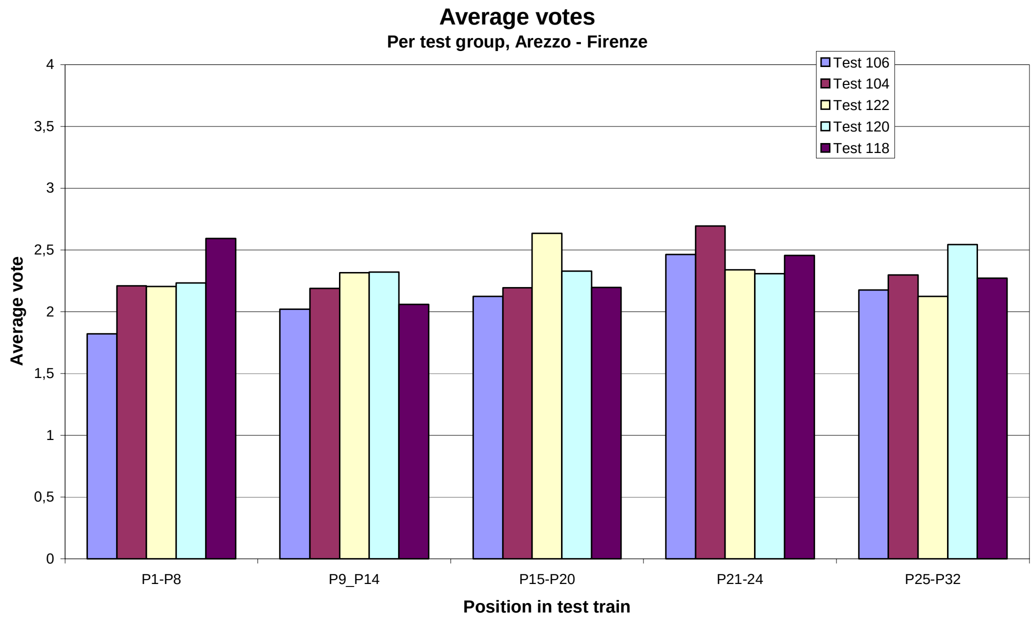


Figure 10-3 *Average votes for different groups of positions during the test runs. Comfort scale was from very good comfort (1) to very bad comfort t(5).*

Table 10-4 shows the average voting per position in the test train.

Table 10-4 *Average voting per position in the train for the different directions of test run.*

VOTE

Position	Direction	Mean	*N*	Std. Deviation
Rac I	Arezzo–Firenze	2.233	142	0.616
	Firenze–Arezzo	2.788	176	0.716
	Total	2.540	318	0.727
Rac II	Arezzo–Firenze	2.282	142	0.741
	Firenze–Arezzo	2.464	176	0.688
	Total	2.383	318	0.717
BB I	Arezzo–Firenze	2.442	142	0.570
	Firenze–Arezzo	2.306	176	0.690
	Total	2.367	318	0.642
BB m	Arezzo–Firenze	2.361	142	0.530
	Firenze–Arezzo	2.295	176	0.621
	Total	2.324	318	0.582
BB II	Arezzo–Firenze	2.227	142	0.515
	Firenze–Arezzo	2.587	176	0.706
	Total	2.426	318	0.652
Bac I	Arezzo–Firenze	2.413	142	0.602
	Firenze–Arezzo	2.361	176	0.631
	Total	2.384	318	0.618
Bac II	Arezzo–Firenze	2.229	142	0.424
	Firenze–Arezzo	2.582	176	0.648
	Total	2.425	318	0.585
Total	Arezzo–Firenze	2.312	994	0.583
	Firenze–Arezzo	2.483	1232	0.691
	Total	2.407	2226	0.651

Note: "I" denotes the first bogie in the direction of the test runs and "II" denotes the second bogie, while "m" denotes the mid-body position.

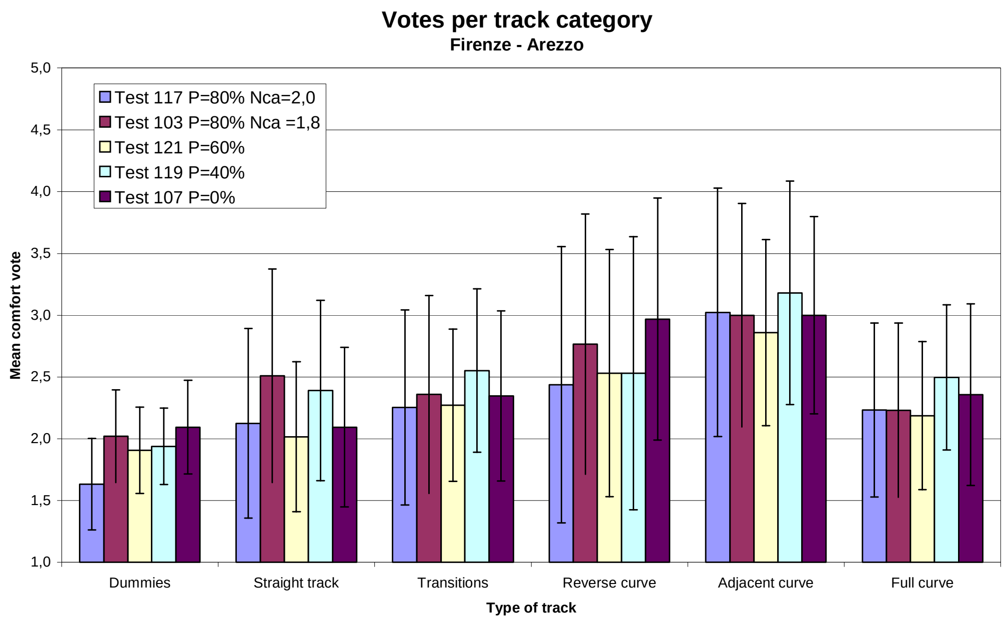
10.4 Track elements

Votes during the test runs related to conditions for different types of selected track element. There were quite different numbers of these types of track elements for the different test directions, as shown in Table 10-5.

Table 10-5 *Number of different track test elements for two directions.*

Type of track	Number of occasions	
	Firenze–Arezzo	Arezzo–Firenze
Dummy	4	5
Straight	2	2
Transition curves	15	15
Reverse transitions	4	2
Adjacent transitions	4	4
Circular curves	7	8

Average votes for the different track categories are shown in Figure 10-4.



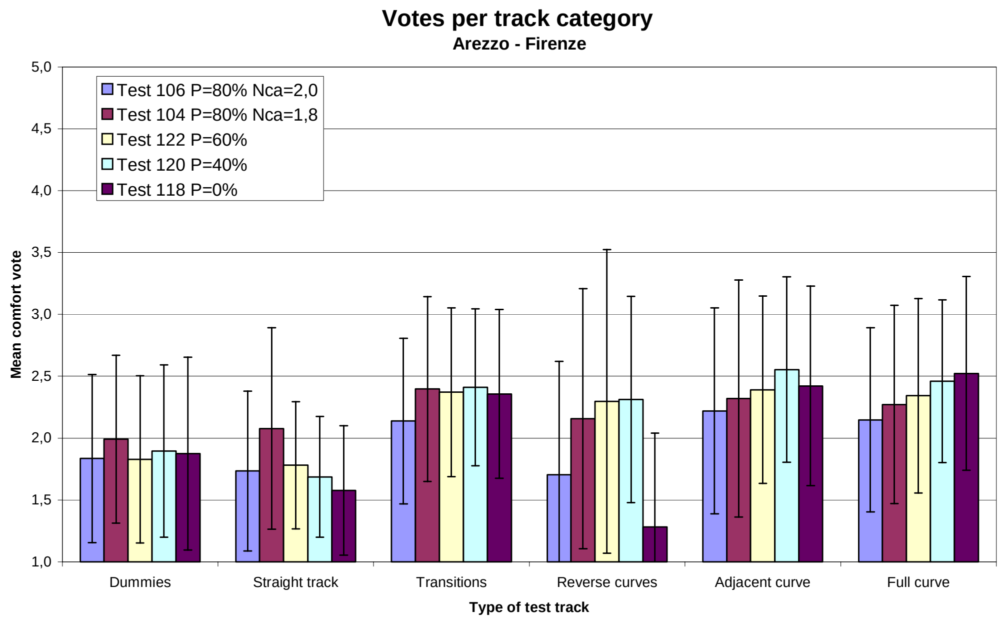


Figure 10-4 *Average votes for the different track categories. Comfort scale was from very good comfort (1) to very bad comfort t(5).*

10.5 Evaluation of measured data

10.5.1 Transitions

The correlation between some evaluated quantities and average votes per train position is shown in Table 10-6 to Table 10-8.

Table 10-6 *Correlation between some evaluated motion quantities and averaged vote per train position, Firenze–Arezzo.*

Quantity/ Evaluation time	Lat acc *y''max*	Lat jerk *Jmax*	Roll vel *φ´max*	Roll acc *φ´´ max*	P_{CT} P_{CT} *max*
0.1 s	0.46	0.52	0.29	0.41	0.60
0.4 s	0.44	0.55	0.28	0.36	0.60
1.0 s	0.43	0.49	0.30	0.31	0.53

Table 10-7 *Correlation between some evaluated motion quantities and averaged vote per train position, Arezzo–Firenze.*

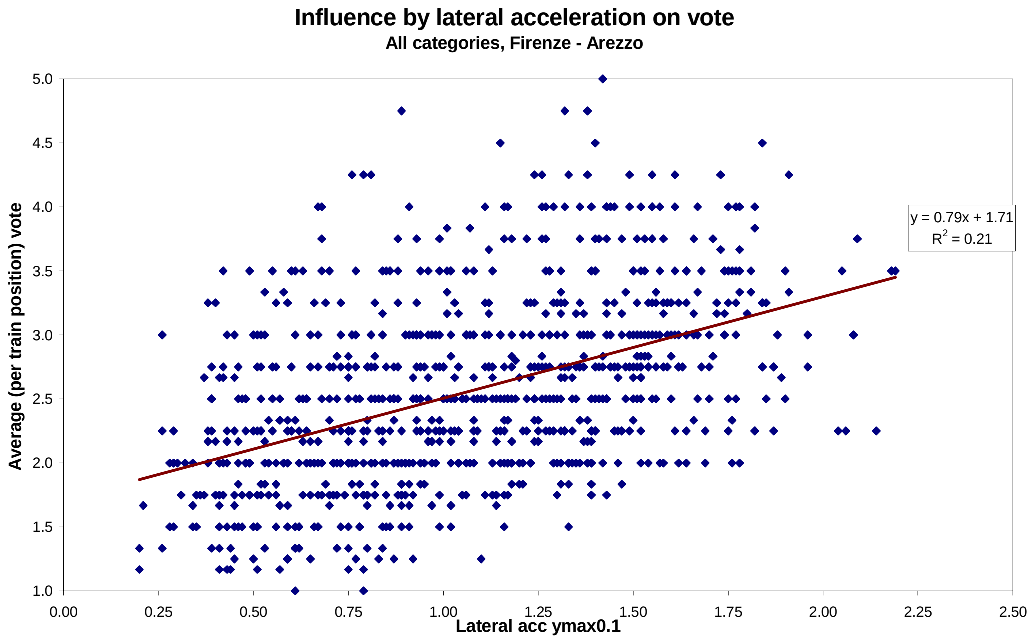
Quantity/ Evaluation time	Lat acc *y''max*	Lat jerk *Jmax*	Roll vel *φ´max*	Roll acc *φ´´ max*	P_{CT} P_{CT} *max*
0.1 s	0.48	0.333	0.12	0.22	0.43
0.4 s	0.47	0.335	0.11	0.19	0.45
1.0 s	0.46	0.29	0.10	0.17	0.43

Table 10-8 *Correlation between some other motion quantities and average vote per train position.*

Quantity	*Nva*	*Nca*	*Y''mean*	*Y''peak*	*Pde*
Firenze–Arezzo	0.41	0.42	0.34	0.31	0.46
Arezzo–Firenze	0.41	0.37	0.59	0.32	0.62

It seems that P_{CT} and P_{DE} are the best candidates for regression models, otherwise the lateral acceleration, jerk and roll acceleration as well as *N'va*.

Figures 10-5 to 10-10 show the influence of a single motion quantity on averaged vote per train position.



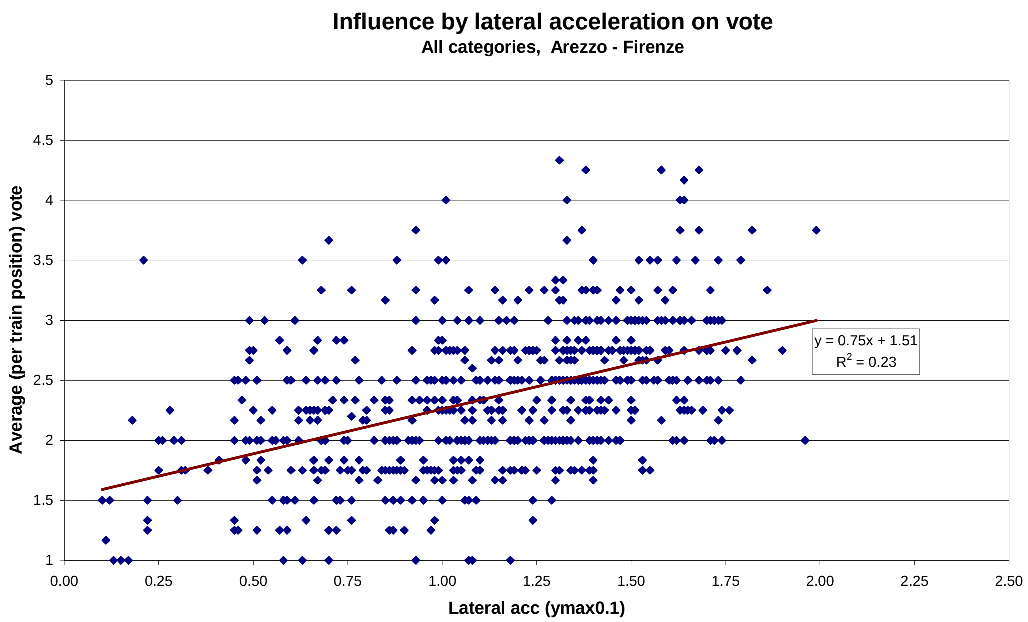
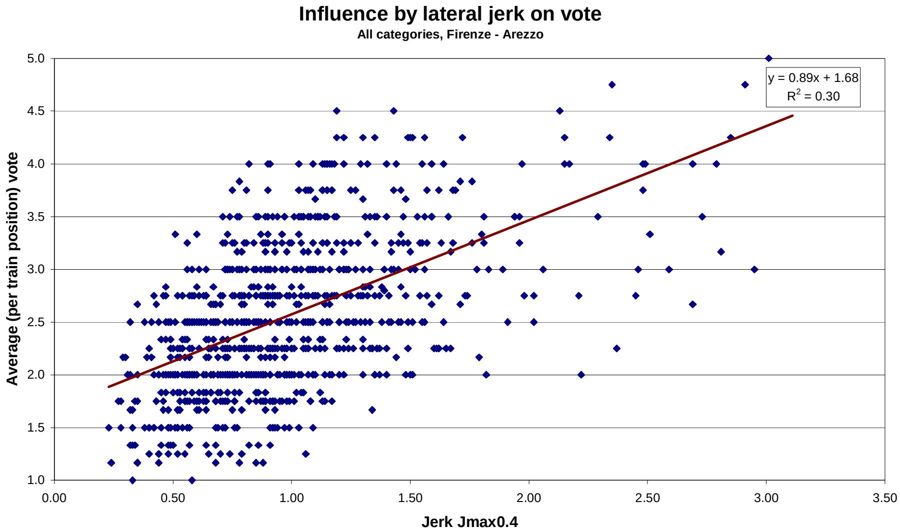


Figure 10-5 *Influence of lateral acceleration on average vote per test direction.*



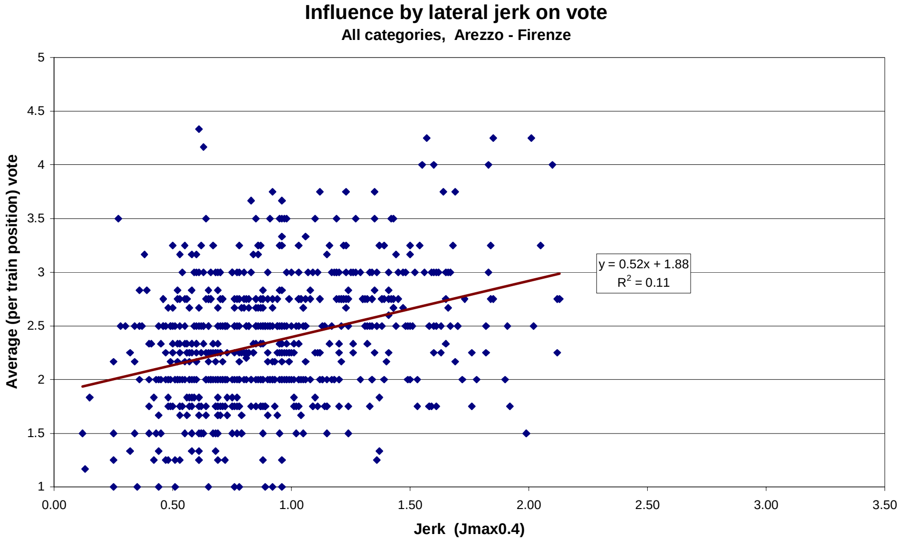
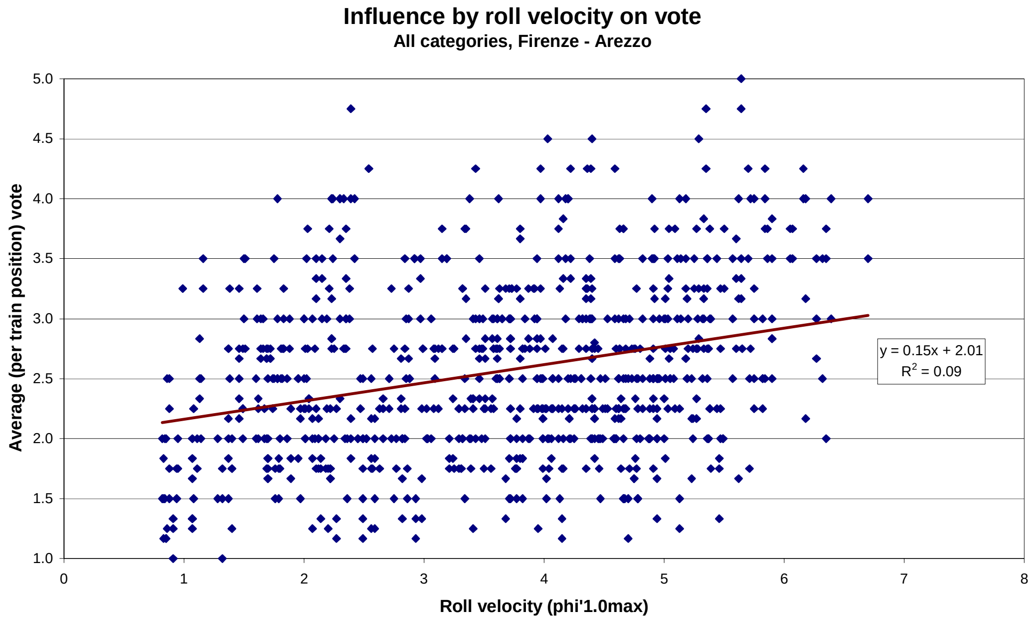


Figure 10-6 *Influence of lateral jerk on average vote per test direction.*



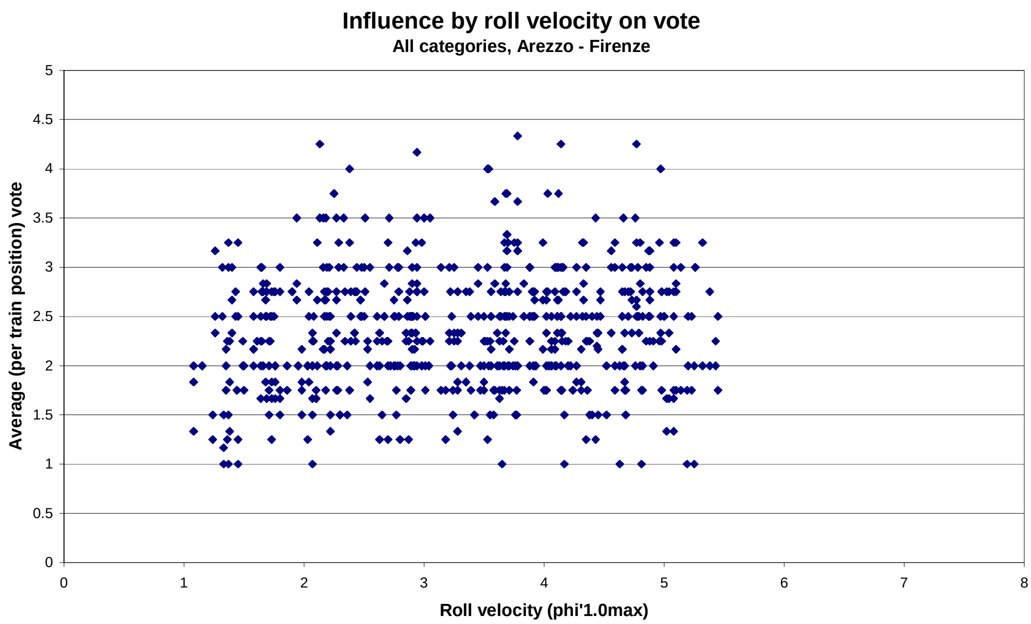
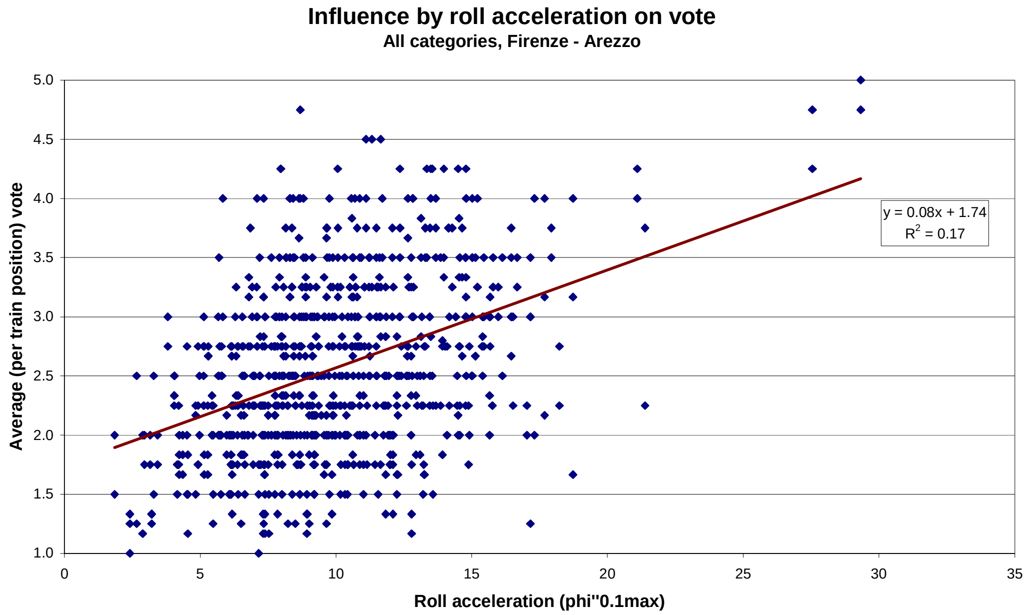


Figure 10-7 *Influence of roll velocity on average vote per test direction.*



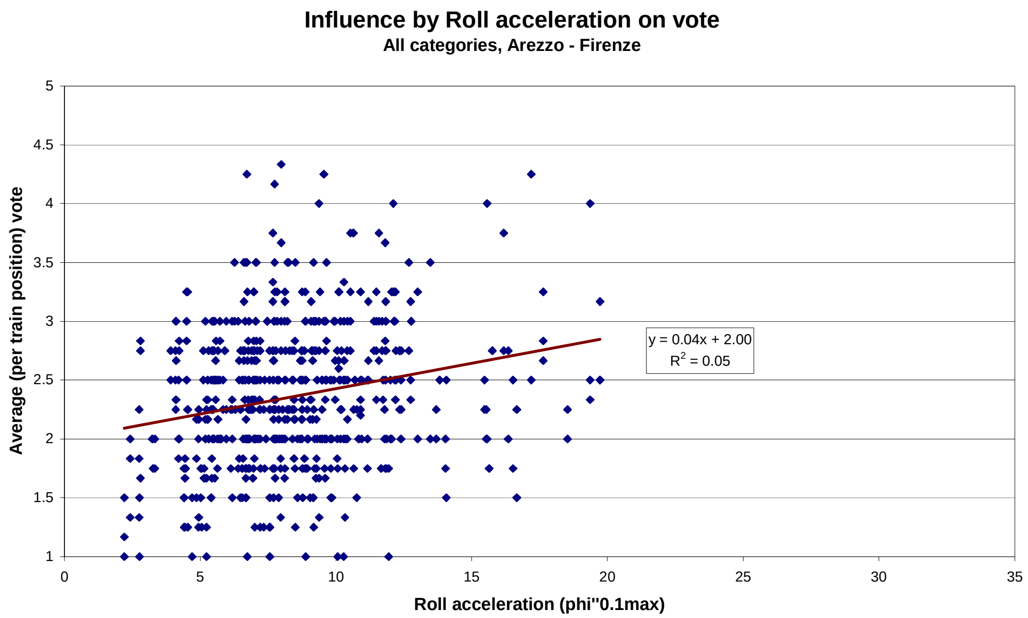
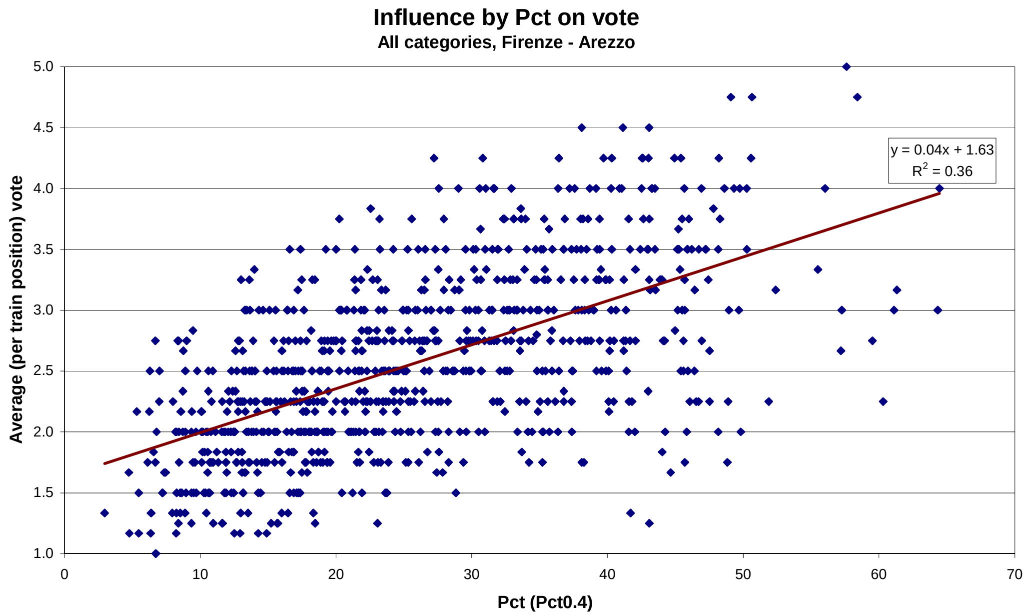


Figure 10-8 *Influence of roll acceleration on average vote per test direction.*



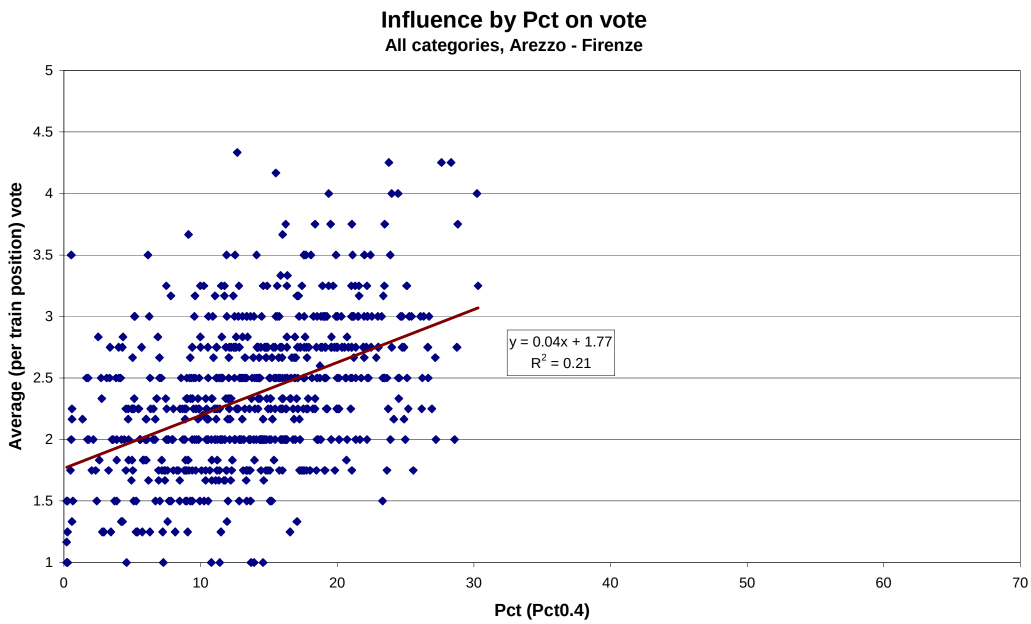
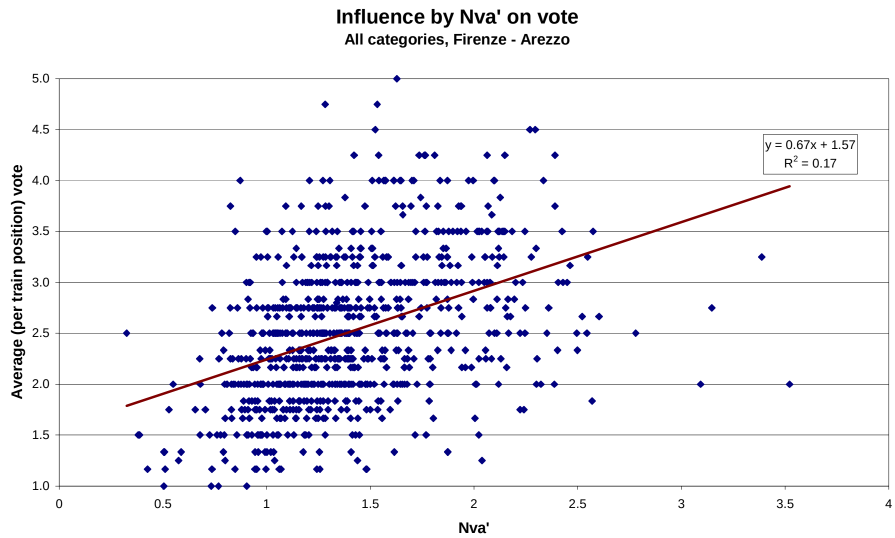


Figure 10-9 ***Influence of P_{CT} on average vote per test direction.***



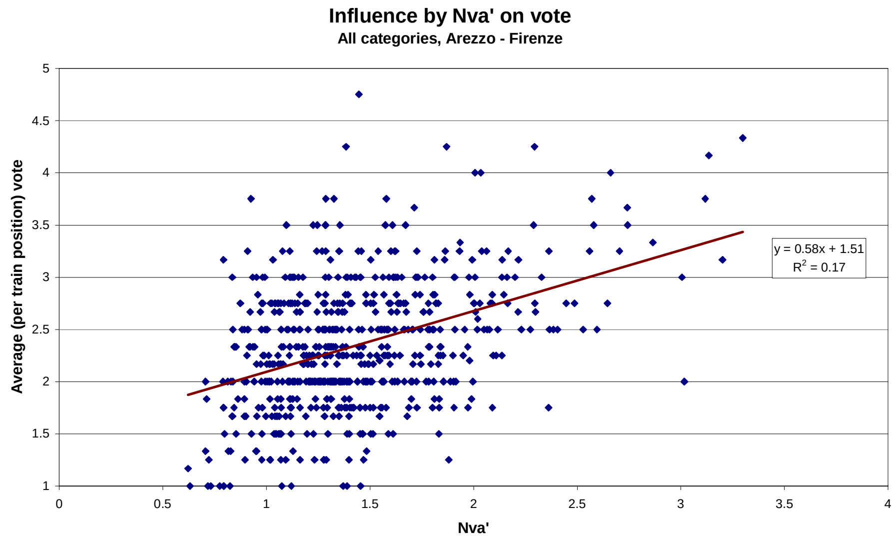


Figure 10-10 *Influence of Nva' on average vote per test direction.*

11 Evaluation of local comfort

11.1 Analysis of Transition response

11.1.1 Types of transition

Measurements were made on several different types of transition.

- simple transitions – from straight track into a curve
- reverse transitions – directly from a curve of one hand to a curve of the opposite hand
- compound transitions – from a larger radius to a tighter radius curve of the same hand
- adjacent transitions – from a curve of one hand to a curve of either the same hand or the opposite hand with a short length of straight track in between
- short transition – this was a location with a very short curve where there was an entry transition, a very short curve and a run-off transition, all within the test zone.

Most measurements (fifteen in each direction) were made on simple transitions. Up to four measurements in each direction were made on the other types of transition.

The test sites were chosen to give the greatest possible spread of non-compensated acceleration and roll velocity on every test run, with reasonable separation of sites while maintaining a constant speed.

11.1.2 Test Conditions

Test results for all four tilt conditions (80%, 60%, 40% and 0% compensation) were combined into a single dataset for analysis. Both directions of running were included, giving a total of nine test runs (with two 80% runs in one direction).

At each test site, votes and acceleration measurements were available for passengers at five different positions in the train. The votes for each group of passengers were averaged, and the average group vote used in regressions against the measured parameters for that group's location.

The groups at different positions in the train included four, six or eight passengers. In the regression analysis, the average vote for the whole group was used to help to improve the correlation of the results. However, to give the correct weight to each group according to its size, the results for groups of four were included twice in the regression, results for groups of six were included three times and results for groups of eight were included four times.

The combination of test runs, test sites and passenger locations gave a large number of separate observations (despite a few occasions where either the votes or acceleration measurements were not valid). The distribution of the data is shown in the table.

__Table 11-1__ Number of observations for the different test sections.

	Number of locations	Separate observations	Weighted observations
Simple transitions	30	667	2132
Adjacent transitions	8	170	544
Reverse transitions	6	115	365
Compound transitions	7	105	336
Short transitions	2	45	144

11.1.3 Parameters

The parameters that were selected for measurement were based on previous experience of comfort tests on curved track. These were four individually measured parameters, and two derived parameters combining accelerations in different directions.

The four individual parameters that were measured were

- $\ddot{y}_{\max}$ - the maximum value of lateral acceleration in the transition
- $\dddot{y}_{\max}$ - the maximum rate of change of lateral acceleration (or jerk)
- $\dot{\theta}_{\max}$ - the maximum roll velocity
- $\ddot{\theta}_{\max}$ - the maximum roll acceleration

In the existing CEN passenger comfort standard, DD ENV 12299:1999, these parameters are measured with a 1.0 second averaging window. Following the work of the ERRI B207 committee, it has been thought that a shorter averaging window might give better correlation with the comfort votes. Thus the same acceleration parameters have also been calculated using 0.4 second and 0.1 second averaging windows, to give a total of twelve parameters for input into the statistical analysis.

- $\ddot{y}_{1.0\max}$, $\dddot{y}_{1.0\max}$, $\dot{\theta}_{1.0\max}$, $\ddot{\theta}_{1.0\max}$
- $\ddot{y}_{0.4\max}$, $\dddot{y}_{0.4\max}$, $\dot{\theta}_{0.4\max}$, $\ddot{\theta}_{0.4\max}$
- $\ddot{y}_{0.1\max}$, $\dddot{y}_{0.1\max}$, $\dot{\theta}_{0.1\max}$, $\ddot{\theta}_{0.1\max}$

Two further parameters were derived from a combination of different acceleration measurements.

N'_{VA} is a derived parameter representing the general ride comfort in the test zone. A comfort weighting filter is applied which eliminates low frequency effects including any influence of the transition curve.

The second derived parameter was P_{CT}, a measure of comfort in curve transitions calculated according to DD ENV 12299:1999 Annex L. It is derived from $\ddot{y}_{1.0\max}$, $\dddot{y}_{1.0\max}$ and $\dot{\theta}_{1.0\max}$ according to the formula:

Equation 11-1 $$P_{CT} = (8.87 \cdot \ddot{y}_{1.0\max} + 13.05 \cdot \dddot{y}_{1.0\max} - 5.9) - 0.120 * \dot{\theta}_{1.0\max}^{1.626}$$

11.1.4 Scaling of votes

The N'_{VA} parameter is derived on a scale from 0 to 5. However, in the current test, the votes were based on push buttons scaling from 1 to 5. The votes from the current test were converted to the same scale as the N'_{VA} parameter, by the formula

Scaled vote = 1.25 * (measured vote – 1)

11.1.5 Examination of votes

To check that all test persons were undertaking their task conscientiously, the votes were examined. Tables of votes from each of the tests were given a brief visual check to look for any obvious anomalies such as always voting the same, or obviously random votes. In most test runs there were a few "lost" votes, but no other problems were seen.

The votes from two test runs were subjected to more detailed analysis. This included checking the mean and standard deviation of each test person's votes for all the test sites in the run. For run 106 (80% compensation), the mean votes for each test person varied from 1.45 to 2.83, with standard deviations ranging from 0.45 to 0.96. For run 118 (non-tilting), the mean votes for each test person varied from 1.87 to 2.87, with standard deviations ranging from 0.48 to 1.23.

In principle, a high standard deviation is a good thing, as a wide spread of votes can give a more accurate statistical regression. However, the spread of votes is only helpful if they reflect the actual comfort, rather than a random response.

The possibility of a random response can be tested by comparing a test person's votes with the general trend of all of the test persons. Each test person's vote at a test location is normalised by subtracting the mean vote of all test persons at that location. If an individual's votes are following the general trend, then the standard deviation of their normalised votes should be less than the standard deviation of their original votes.

This test was carried out for runs 106 and 118. For run 106, most test persons' normalised votes had a standard deviation that was less than the standard deviation of original votes, but five were higher, by at most 15%. For run 118 two test persons had a standard deviation of the normalised votes higher than the original standard deviation, by up to 10%.

As the test persons changed position between tests, it was not possible to confirm whether the same persons were responsible for the "poor quality" votes in both test runs. It is of course also possible that they genuinely had a response that was different from the average. As the votes for each group were averaged in the analysis, it was felt that the influence of the few "poor quality" votes would not significantly affect the accuracy of the analysis.

11.1.6 Examination of data – simple transitions

Before undertaking multiple regression analysis, it is advisable to make a visual examination of the data, looking at relationships between the parameters and votes, and looking for any relationships between parameters. This exercise has been undertaken initially for the simple transition data.

Figure 11-1shows the votes (averaged for each position) plotted against the values of the derived parameters N'_{VA} and P_{CT} in the form of scatter plots. Data for each tilt compensation level are differentiated by colour. The best-fit line from a single-parameter regression is also shown.

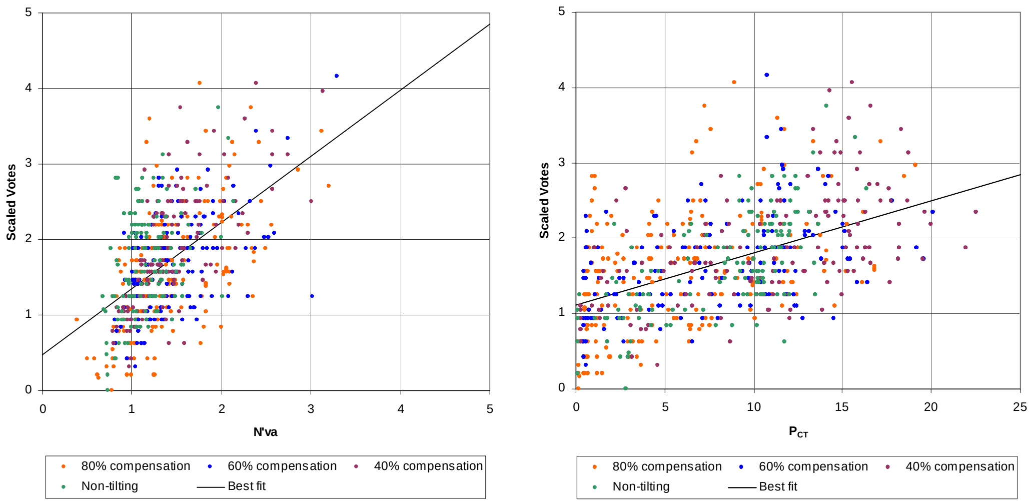


Figure 11-1 *Scatter plots - votes against N'_{VA} and P_{CT}.*

Both the derived measurements are intended to represent ride quality, so that some correlation with the recorded votes could be expected. In fact the correlation coefficients are 0.536 for N'_{VA} and 0.517 for P_{CT}.

If the current measurements corresponded with the results of the earlier ERRI B153 tests, the scaled votes would have a 1:1 correspondence with the N'_{VA} parameter, and the best-fit line would pass through the origin. The non-zero intercept is an indication that other factors are also affecting the comfort in the curve transitions.

Single parameter regressions were also made for the individual parameters, measured with all three averaging windows. The correlation coefficients of the votes against these parameters are shown in Table 11-2.

Table 11-2 *Correlation coefficients - scaled votes against individual parameters.*

	$\ddot{y}_{\max}$	$\dddot{y}_{\max}$	$\dot{\theta}_{\max}$	$\ddot{\theta}_{\max}$
1.0-second base	0.522	0.440	0.268	0.292
0.4-second base	0.541	0.458	0.238	0.247
0.1-second base	0.562	0.492	0.241	0.280

Both lateral parameters have significantly greater correlation with the votes than the roll parameters. Indeed, the maximum lateral acceleration with the shorter averaging windows is better correlated with the votes than are either N'_{VA} or P_{CT}.

The lateral parameters show the best correlation to the votes with the 0.1-second window, while the roll parameters show the best correlation with the 1.0-second window. The parameters with a 0.4-second window appear between the two.

The scaled votes are plotted against the four individual parameters (with a 0.1-second window) in Figure 11-2.

Note that very high values of lateral acceleration have been recorded (up to 2.08 m/s^2), even with the train operating with 80% tilt compensation, when the tilt system should be compensating for most of the lateral acceleration. Closer examination shows that the highest values of acceleration are all recorded in the leading vehicle, where the tilt system response might be expected to be worse.

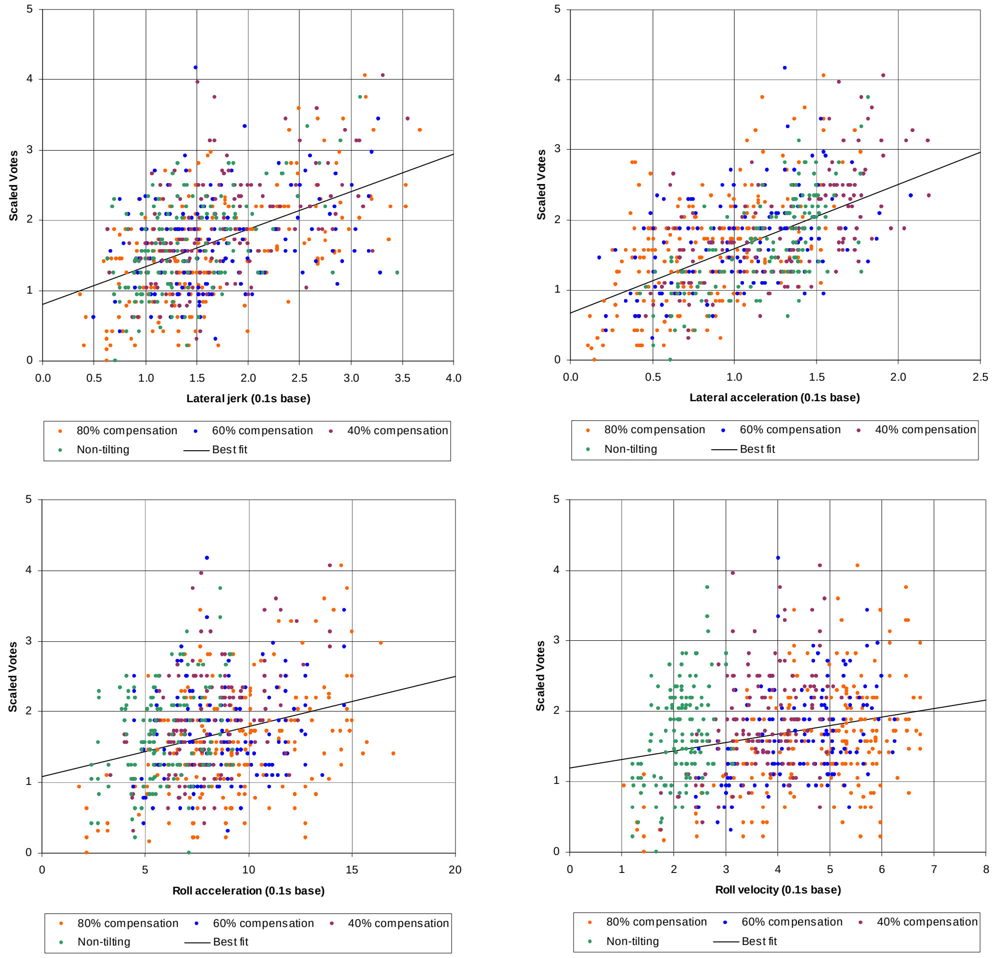


Figure 11-2 *Scatter plots – votes against individual parameters (from left upper to right below: Lateral jerk (0.1s) Lateral acceleration (0.1s), roll acceleration (0.1s) and roll velocity (0.1s)).*

The spread of data clearly justifies the decision to test with 40% and 60% tilt as well as 80%.

11.1.7 Relationship between parameters – simple transitions

As well as understanding the relationships of the measured parameters to the recorded votes, it is also important to understand the relationships of the parameters with each other. If two parameters are strongly correlated with each other, then including both in the same multiple regression will give invalid results.

The P_{CT} parameter is derived directly from three of the individual parameters used in this study, so it can only be used in a regression with N'_{VA}, and not with any of the individual parameters.

Single parameter regressions of N'_{VA} and the individual parameters against each other yield the correlation coefficients given in Table 11-3, for the parameters measured on a 1.0-second base.

***Table 11-3** Correlation coefficients - votes against 1.0-second parameters.*

	$\ddot{y}_{1.0\max}$	$\dddot{y}_{1.0\max}$	$\dot{\theta}_{1.0\max}$	$\ddot{\theta}_{1.0\max}$
N'_{VA}	0.294	0.322	0.379	0.359
$\ddot{y}_{1.0\max}$		**0.819**	0.161	0.124
$\dddot{y}_{1.0\max}$			0.315	0.252
$\dot{\theta}_{1.0\max}$				**0.879**

For the 1.0-second data the lateral jerk and the lateral acceleration are strongly correlated. This is a problem, as the lateral jerk is the main parameter that takes into account the length of the transition. The jerk is important if the comfort measure is to be used as guidance for appropriate transition lengths.

The roll acceleration and roll velocity are also strongly correlated – this may be a feature of the Pendolino tilt system, and may not necessarily apply to all designs of tilting train.

The same correlation coefficients with the data averaged on a 0.1-second window are shown in Table 11-4.

***Table 11-4** Correlation coefficients - votes against 0.1-second parameters.*

	$\ddot{y}_{0.1\max}$	$\dddot{y}_{0.1\max}$	$\dot{\theta}_{0.1\max}$	$\ddot{\theta}_{0.1\max}$
N'_{VA}	0.340	**0.541**	0.347	0.328
$\ddot{y}_{0.1\max}$		0.486	0.140	0.138
$\dddot{y}_{0.1\max}$			0.414	0.460
$\dot{\theta}_{0.1\max}$				**0.741**

With the shorter averaging window, the correlation between the lateral jerk and the lateral acceleration is much less. Conversely, the correlation between the lateral jerk and N'_{VA} has increased and is now quite significant. The roll velocity and roll acceleration are still closely correlated.

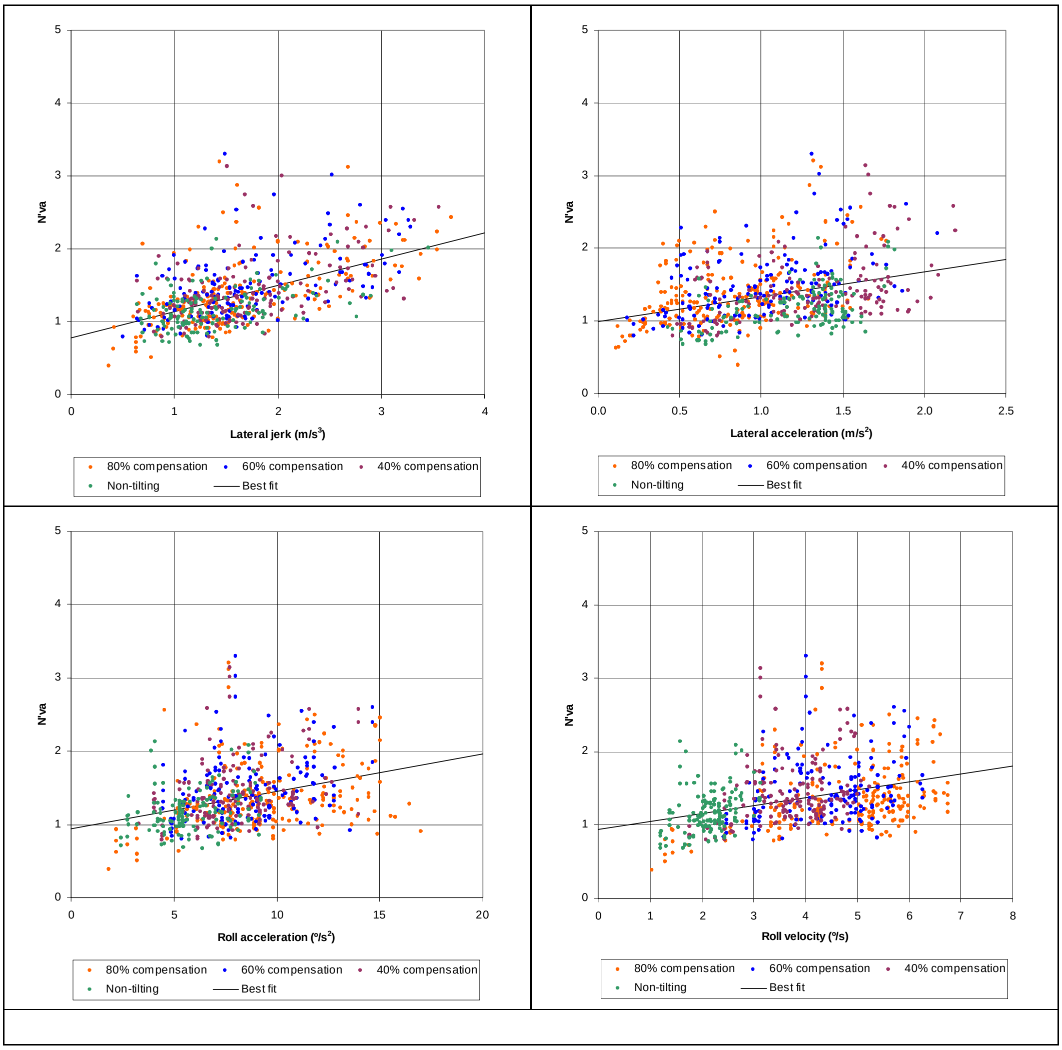


Figure 11-3 *Scatter plots – N'VA against individual parameters (from left upper to right below: Lateral jerk (0.1s) Lateral acceleration (0.1s), roll acceleration (0.1s) and roll velocity (0.1 s)).*

Figure 11-3 shows N'_{VA} plotted against the individual parameters calculated with a 0.1-second window. The correlation between N'_{VA} and lateral jerk can be clearly seen.

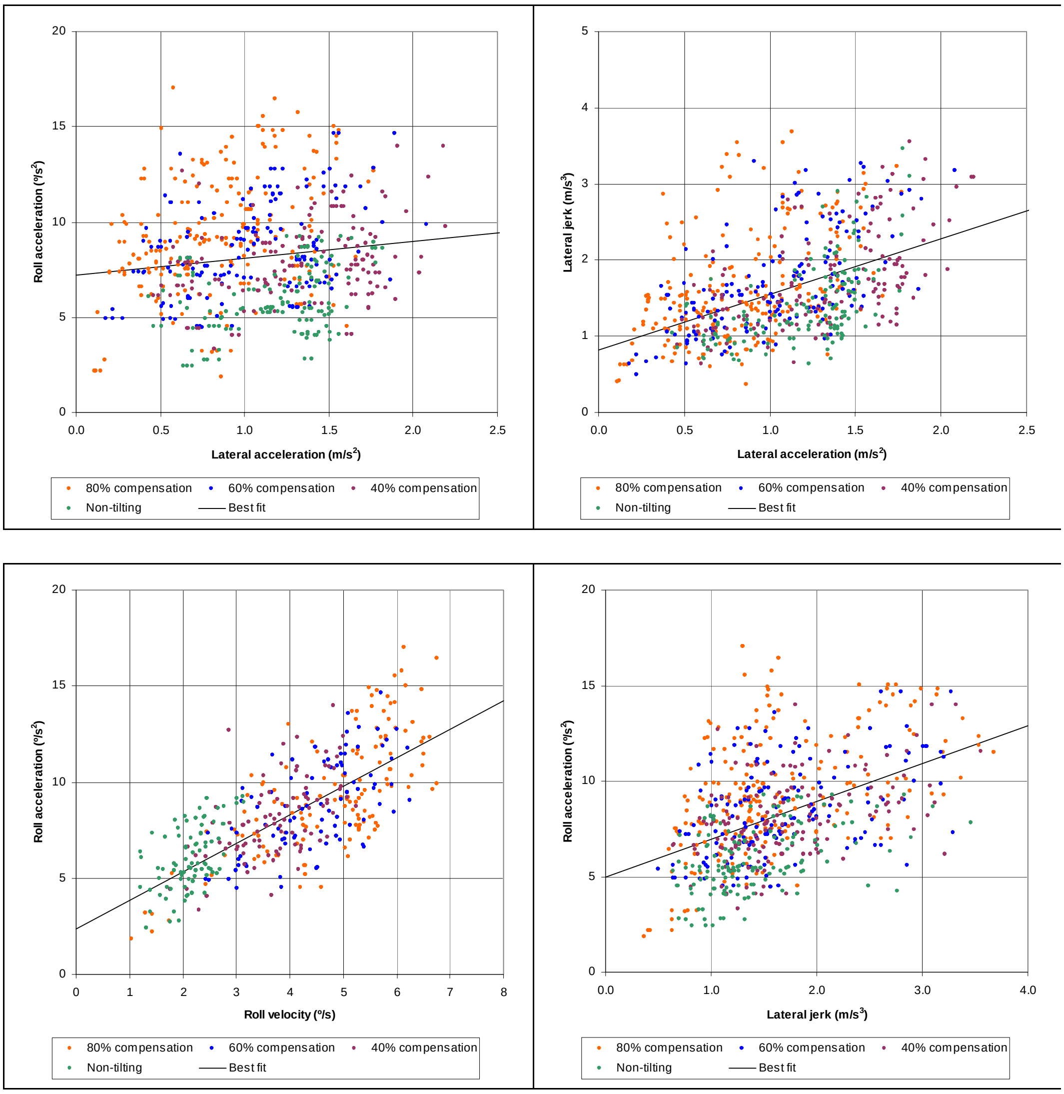


Figure 11-4 *Scatter plots – individual parameters.*

A selection of the relationships between the individual parameters, again calculated with 0.1-second averaging, is shown in Figure 11-4.

The increased spread of the data from using three different tilt compensation levels can clearly be seen in the plot of roll acceleration against lateral acceleration.

The correlation between roll acceleration and roll velocity can be clearly seen. These two parameters are so closely correlated that it does not seem possible to treat them as independent. It was therefore decided not to include both these parameters in the same regression.

11.1.8 Regression analysis – simple transitions

A two-parameter regression combining N'_{VA} and P_{CT} gave the results shown in Table 11-5. The correlation is significantly better than the single parameter regressions.

Table 11-5 *Two-parameter regression - N'_{VA} and P_{CT}.*

Object: Simple transitions				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.645	756.1	2129
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.668	23.2	55%
	P_{CT}	0.051	21.6	24%
	Intercept	0.348	8.9	21%

The t-value is a measure of the significance of each parameter in the regression. In this case both N'_{VA} and P_{CT} have high *t*-values, and the intercept also cannot be ignored.

The column showing typical contribution for each parameter shows the result of multiplying the average value of the parameter by the coefficient. This gives an indication of the contribution of each term in the regression equation to a typical predicted vote.

Figure 11-5 shows the quality of the regression as a plot of predicted against measured votes.

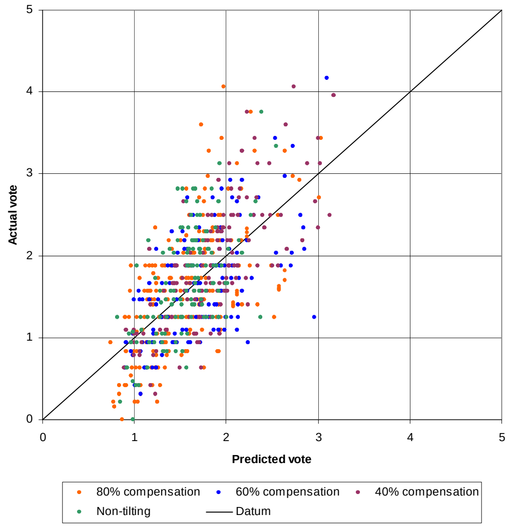


Figure 11-5 *Quality of two-parameter regression, N'_{VA} and P_{CT}.*

Although P_{CT} is a measure of comfort in curve transitions, it is based on a single threshold of dissatisfaction, rather than the linear comfort scale of the current tests. Although P_{CT} should have some correlation with the votes in the current test, it is likely that a better correlation could be obtained with a different combination of the parameters measured in these tests.

Multiple regressions have therefore been undertaken including *N'*$_{VA}$ and the individual parameters. As the roll velocity and roll accelerations were strongly correlated, multiple regressions were undertaken using either the roll velocity or the roll acceleration, but not both together. Regressions were undertaken for each of the three different averaging periods, see Table 11-6.

Table 11-6 *Multiple parameter regressions – roll velocity parameter.*

Object: Simple transitions with roll velocity and 1.0 second averaging				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.662	415.2	2129
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.657	22.1	+54%
	$\ddot{y}_{1.0\max}$	0.823	23.0	+47%
	$\dddot{y}_{1.0\max}$	-0.348	-3.4	-9%
	$\dot{\theta}_{1.0\max}$	0.040	3.9	+8%
	Intercept	-0.001	0.0	0%

Object: Simple transitions with roll velocity and 0.4 second averaging				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.669	429.1	2129
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.627	21.1	+51%
	$\ddot{y}_{0.4\max}$	0.639	18.0	+39%
	$\dddot{y}_{0.4\max}$	0.130	2.6	+7%
	$\dot{\theta}_{0.4\max}$	0.018	1.8	+4%
	Intercept	-0.019	-0.4	-1%

Object: Simple transitions with roll velocity and 0.1 second averaging				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.678	451.6	2129
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.547	17.3	+45%
	$\ddot{y}_{0.1\max}$	0.637	21.2	+42%
	$\dddot{y}_{0.1\max}$	0.121	5.2	+11%
	$\dot{\theta}_{0.1\max}$	0.012	1.3	+3%
	Intercept	-0.008	-0.18	-1%

The results using the roll velocity parameter are shown Table 11-7. The correlation improves slightly as the averaging window of the data reduces.

Table 11-7 *Multiple parameter regressions - roll acceleration parameter.*

Object: Simple transitions with roll acceleration and 1.0 second averaging				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.669	429.2	2129
	Probability	< 0.1%	<0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.631	21.5	+51%
	$\ddot{y}_{1.0\max}$	0.842	17.1	+49%
	$\dddot{y}_{1.0\max}$	-0.389	-3.9	-10%
	$\ddot{\theta}_{1.0\max}$	0.072	6.8	+14%
	Intercept	-0.073	-1.6	-4%

Object: Simple transitions with roll acceleration and 0.4 second averaging				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.672	437.4	2129
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.619	21.4	+51%
	$\ddot{y}_{0.4\max}$	0.665	18.6	+41%
	$\dddot{y}_{0.4\max}$	0.062	1.2	+3%
	$\ddot{\theta}_{0.4\max}$	0.032	4.7	+10%
	Intercept	-0.088	-1.9	-5%

Object: Simple transitions with roll acceleration and 0.1 second averaging				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.681	459.4	2129
	Probability	<0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.539	17.3	+44%
	$\ddot{y}_{0.1\max}$	0.649	21.2	+42%
	$\dddot{y}_{0.1\max}$	0.092	3.8	+9%
	$\ddot{\theta}_{0.1\max}$	0.02	4.3	+10%
	Intercept	-0.077	-1.7	-5%

With the 1.0-second window, the jerk term $\dddot{y}_{1.0\max}$ appears with a negative coefficient. This is not physically believable, and is probably a consequence of the correlation between the jerk and the lateral acceleration $\ddot{y}_{1.0\max}$ with the 1.0-second window.

From the *t*-value, N'_{VA} and the lateral acceleration are the most important parameters. The importance of the jerk increases as the averaging window reduces, but is always less. The roll velocity has almost no importance in any of the regressions.

The results using the roll acceleration parameter are shown in Table 11-7.

Using roll acceleration rather than roll velocity slightly improves the correlation, and the t-value indicates greater significance for the roll acceleration terms than the roll velocity terms. Conversely, the jerk term becomes even less significant when the roll acceleration is used.

The best correlation is found with the roll acceleration, using parameters based on a 0.1-second averaging window.

Table 11-8 shows the result of repeating the regression for the preferred case, with the intercept forced to zero. This is reasonable as the *t*-value for the intercept is very small. It is also desirable, as it means that the comfort index becomes zero for zero inputs.

Table 11-8 *Multiple regression – zero intercept.*

Object: Simple transitions with roll acceleration and 0.1 second averaging				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.681	458.3	2129
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.517	18.2	42%
	$\ddot{y}_{0.1\max}$	0.631	22.5	41%
	$\dddot{y}_{0.1\max}$	0.096	4.0	9%
	$\ddot{\theta}_{0.1\max}$	0.016	4.0	8%

Forcing the result through zero leaves the correlation unchanged, and the ranking of the various terms by the *t*-value remains similar to before, with the N'_{VA} and lateral acceleration terms of approximately equal importance, while the lateral jerk and roll acceleration are also of equal, but much less importance. The quality of the regression is shown in Figure 11-6.

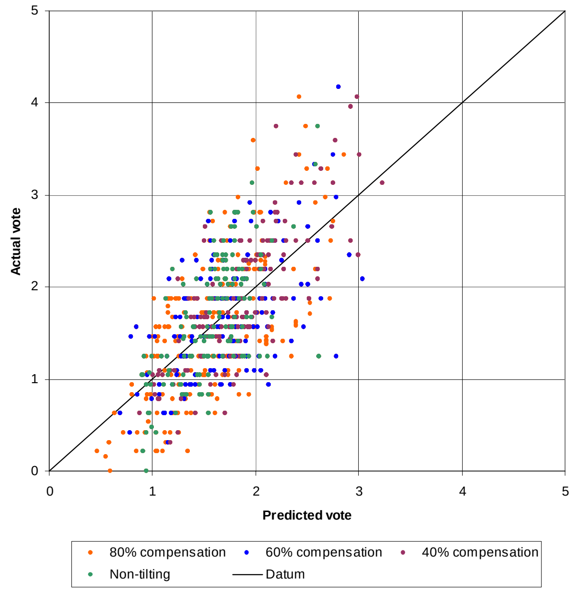


Figure 11-6 *Quality of multiple parameter regression.*

11.1.9 Investigation of leading vehicle effects

In a tilting train the leading vehicle is the most difficult in which to achieve an acceptable tilt system response, because it is the first vehicle to reach the curve, and it is difficult to compensate for the effect of delays in the acceleration sensing and tilt control system.

To find whether the character of the response of the leading vehicle is significantly different, and whether this significantly affects the final results, the regression has been repeated with the results for the leading vehicle eliminated from the database.

The results of the regression are shown in Table 11-9, which can be directly compared with the results already given in Table 11-8.

Table 11-9 *Multiple regression – excluding leading vehicle.*

Object: Simple transitions without leading vehicle				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.720	427.8	1527
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.652	19.6	+53%
	$\ddot{y}_{0.1\max}$	0.677	21.0	+44%
	$\dddot{y}_{0.1\max}$	0.049	1.8	+5%
	$\ddot{\theta}_{0.1\max}$	-0.003	-0.7	-2%

The correlation is significantly improved by removing the data for the leading vehicle, but also the significance of the lateral jerk and roll acceleration parameters has become much less.

The regression has been repeated without the lateral jerk and roll acceleration terms, as shown in Table 11-10.

Table 11-10 *Two-parameter regression – excluding leading vehicle.*

Object: Simple transitions without leading vehicle				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.719	853.2	1527
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.673	29.8	55%
	$\ddot{y}_{0.1\max}$	0.699	23.9	45%

The correlation is only very slightly reduced by reducing the regression to the two parameters.

Although removing the leading vehicle from the regression improves the quality of the regression, the all-vehicle regression gives a result that is probably more general in its application, and still gives an acceptable correlation.

11.1.10 Effect of other transition types

The analysis so far has included only the results for simple transitions.

From the work of BR Research that led to the P_{CT} measure, the character of the passenger response to reverse and compound transitions is different to simple transitions. For a given set of parameters, passengers were found to be more tolerant of reverse transitions and less tolerant of compound transitions than they were of simple transitions.

The differing responses are due to passenger expectations and preparedness. A simple entry transition follows a period of straight track, and comes without warning, giving a high risk of throwing the passenger off-balance. Once the passenger is in the curve, an exit transition is expected and hence causes no significant discomfort. In a reverse curve, the passenger is already expecting the exit transition, and the immediately following entry transition is a continuation of an already-expected event. Conversely, a compound transition occurs in an unexpected direction, and may cause additional upset.

In the current study, the lack of preparedness of the passenger will be compromised by the use of a warning signal for the start of the voting period. This may change the relative ranking of the transition events. The study also included “adjacent” transitions and “short” transition, which are cases not studied in the earlier work.

Table 11-11 shows the mean values of the scaled vote and the main measured parameters for each type of transition, and the correlation between the parameters and the votes.

By comparison with the simple transitions considered so far in the study, the adjacent transitions have a higher mean vote, and higher mean values of all parameters, particularly the lateral jerk. The Adjacent transition votes are less well correlated with N'_{VA} and lateral acceleration, but better correlated with roll acceleration.

Table 11-11 Conditions at different transition types.

		Simple	Adjacent	Reverse	Compound	Short
Vote	Mean	1.66	2.24	1.90	2.14	1.66
N'_{VA}	Mean	1.36	1.45	1.41	1.63	1.38
	Correlation	0.536	0.347	0.527	0.122	0.011
$\ddot{y}_{0.1\max}$	Mean	1.08	1.27	1.03	1.24	0.86
	Correlation	0.562	0.272	0.284	0.208	0.016
$\dddot{y}_{0.1\max}$	Mean	1.61	2.72	2.12	3.11	1.76
	Correlation	0.492	0.494	0.676	0.030	0.022
$\ddot{\theta}_{0.1\max}$	Mean	8.17	12.21	8.24	11.33	10.06
	Correlation	0.280	0.401	0.462	0.162	0.458

Compared to the simple transitions, the reverse transitions have similar mean levels of the main parameters, apart from rather higher lateral jerk. The votes are generally higher, and less well correlated to the lateral acceleration, but particularly well correlated to lateral jerk.

Compared to the simple transitions, the compound transitions have higher mean levels of the main parameters, particularly the lateral jerk. The votes are also higher, but show very poor correlation with all the main parameters, and the best-fit lines from the regressions are in some cases negative, indicating unsatisfactory data.

Compared to the simple transitions, the short transitions have similar levels of the main parameters, and the mean votes are the same. However, the votes show very poor correlation with all of the main parameters, apart from the roll acceleration, and the best-fit lines from the regressions are in some cases again negative, indicating unsatisfactory data.

Table 11-12 shows the effects of adding the other types of transition to the regression, in turn.

Table 11-12 Multiple parameter regressions – roll acceleration parameter.

Object: Simple transitions				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.681	458.3	2129
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.517	18.2	42%
	$\ddot{y}_{0.1\max}$	0.631	22.5	41%
	$\dddot{y}_{0.1\max}$	0.096	4.0	9%
	$\ddot{\theta}_{0.1\max}$	0.016	4.0	8%

(Table 11-12)

Object: Simple and adjacent transitions				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.685	591.0	2673
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.372	14.3	28%
	$\ddot{y}_{0.1\max}$	0.590	22.9	37%
	$\dddot{y}_{0.1\max}$	0.204	11.8	21%
	$\ddot{\theta}_{0.1\max}$	0.027	7.5	14%

Object: Simple, adjacent and reverse transitions				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.692	698.4	3038
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.391	15.8	30%
	$\ddot{y}_{0.1\max}$	0.569	23.3	35%
	$\dddot{y}_{0.1\max}$	0.237	15.0	24%
	$\ddot{\theta}_{0.1\max}$	0.022	6.2	11%

Object: Simple, adjacent and reverse and compound transitions				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.661	653.5	3374
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.390	16.0	30%
	$\ddot{y}_{0.1\max}$	0.635	27.2	39%
	$\dddot{y}_{0.1\max}$	0.163	11.6	17%
	$\ddot{\theta}_{0.1\max}$	0.028	8.2	14%

(Table 11-12)

Object: All transitions				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.651	645.0	3518
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.383	15.8	30%
	$\ddot{y}_{0.1\max}$	0.635	27.2	38%
	$\dddot{y}_{0.1\max}$	0.146	10.5	16%
	$\ddot{\theta}_{0.1\max}$	0.032	9.9	16%

Adding the adjacent transitions to the regression, the coefficient and the importance of the N'_{VA} term are reduced, while the coefficient and the importance of the lateral jerk and roll acceleration both increase. The correlation improves slightly.

Adding the reverse transitions reinforces these changes, with the coefficient and the importance of the lateral jerk increasing further, and a further slight improvement in correlation.

Adding the compound transitions and the short transitions reduce the correlation slightly, and boost the importance of the lateral and roll acceleration terms at the expense of the lateral jerk.

The regression using all transitions is the one selected by the Working Group as the best formulation to represent passenger comfort in transitions.

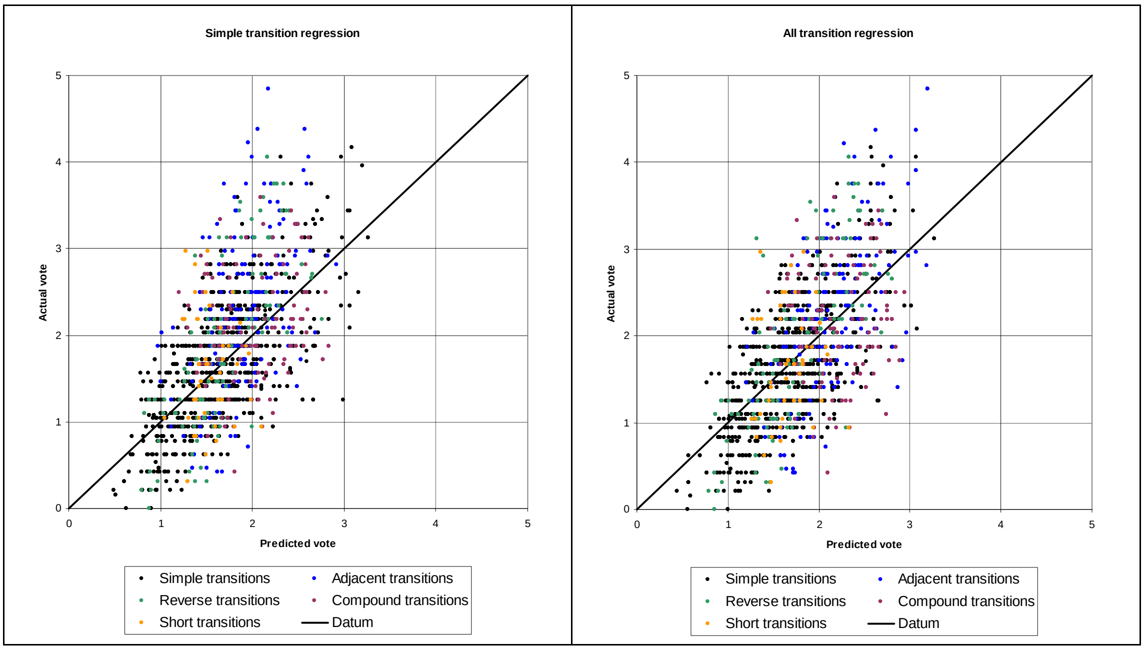


***Figure 11-7** Comparison of regressions – simple and all transitions.*

Figure 11-7 shows the quality of the regression, by plotting actual against predicted vote for all of the transition types. Two cases are compared, with the predicted votes calculated using the regression equation derived only from the simple transitions, and with the regression equation derived using all the transitions.

The above regressions assume that the intercept is zero. To check whether this is still a valid assumption when the data for all transitions has been included, the regression has been repeated allowing a non-zero intercept, as shown in Table 11-13.

The correlation is very slightly improved but the t-value of the intercept is not large, suggesting that the intercept can be neglected without significant loss of accuracy.

Table 11-13 *Multiple parameter regression with intercept – roll acceleration parameter.*

Object: All transitions				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.652	648.3	3518
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.426	14.9	29%
	$\ddot{y}_{0.1\max}$	0.671	25.3	36%
	$\dddot{y}_{0.1\max}$	0.136	9.5	13%
	$\ddot{\theta}_{0.1\max}$	0.037	10.2	16%
	intercept	-0.124	-2.8	6%

The effect of using roll velocity instead of roll acceleration has also been investigated, as shown in Table 11-14. The correlation is slightly less, and the t-value of the roll velocity is significantly less than that for the roll acceleration. The intercept is also less important in this case, and could probably be omitted.

Table 11-14 *Multiple parameter regression with intercept – roll velocity parameter.*

Object: All transitions with roll velocity				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.642	616.8	3518
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.425	14.5	31%
	$\ddot{y}_{0.1\max}$	0.659	24.6	38%
	$\dddot{y}_{0.1\max}$	0.186	14.1	19%
	$\dot{\theta}_{0.1\max}$	0.042	5.5	9%
	intercept	-0.047	-1.0	2%

11.1.11 Non-linear regressions

The existing P_{CT} measure uses a non-linear relationship with roll velocity, which is raised to the power of 1.626. This was found to give the best fit with the measured data during the BR Research tests. It was therefore decided to investigate the effect on the regression of raising the parameters to a higher power.

The tables below show the results of multiple regression analysis using the roll acceleration or roll velocity squared or cubed, rather than the unmodified value. This will tend to boost the importance of higher values, and reduce the importance of lower values.

Table 11-15 *Multiple parameter regressions with squared roll parameters.*

Parameter	Correlation	*t*-value for parameter
Roll acceleration	0.652	10.2
(Roll acceleration)^2	0.654	11.3
Roll velocity	0.642	5.5
(Roll velocity)^2	0.644	6.8

In each case raising the roll parameter to a higher power gives slightly better correlation and significantly improves the *t*-value for the parameter.

The same analysis for the lateral acceleration is shown in the following table (for the regression using roll acceleration). In this case using a higher power gives a very marginal improvement.

Table 11-16 *Multiple parameter regressions with squared lateral acceleration.*

Parameter	Correlation	*t*-value for parameter
Lateral acceleration	0.652	25.32
(Lateral acceleration)^2	0.652	25.38

Finally, the same analysis for the lateral jerk is shown in the following table (again for the regression using roll acceleration). In this case using a higher power is slightly worse.

Table 11-17 *Multiple parameter regressions with squared lateral jerk.*

Parameter	Correlation	*t*-value for parameter
Lateral jerk	0.652	9.5
(Lateral jerk)^2	0.651	9.3

The working group concludes that although raising the roll term to a higher power gives a slight improvement to in correlation, the benefit is small, and does not justify the additional complexity in the calculation.

11.1.12 Regression for track engineers

A relationship that can be related to actual track geometry parameters is helpful to allow track engineers to design transition curves. This should exclude the N'_{VA} term and be based on roll velocity rather than roll acceleration.

Table 11-18 *Regression for track engineers with 0.1-second averaging.*

Object: All transitions with roll velocity – 0.1 second averaging				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.614	710.6	3518
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	$\ddot{y}_{0.1\max}$	0.699	25.5	43%
	$\dddot{y}_{0.1\max}$	0.261	21.0	28%
	$\dot{\theta}_{0.1\max}$	0.067	8.7	15%
	intercept	0.254	6.2	14%

The 1.0-second average might be more appropriate than the 0.1-second average, as the average parameters through the transition are all that the track engineer can influence.

Table 11-19 *Regression for track engineers with 1.0-second averaging.*

Object: All transitions with roll velocity – 1.0 second averaging				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.517	428.1	3518
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	$\ddot{y}_{1.0\max}$	0.791	18.9	43%
	$\dddot{y}_{1.0\max}$	0.240	3.2	6%
	$\dot{\theta}_{1.0\max}$	0.129	13.3	25%
	intercept	0.479	11.1	26%

The correlation is less good without N'_{VA} and the 1.0-second window again gives a clearly worse correlation than the 0.1-second window. Nevertheless, the regression with the 1.0-second averaging window is considered to be useful as a guide to track engineers designing transition curves for tilting trains, as all of the parameters can be directly related to the design geometry of the track.

11.1.13 Contribution of diverse regression parameters

In this chapter, data are not weighted to the number of participants in a group.

Probability density of parameters' contribution

The next figure gives the probability of having a contribution of xxx% to the total result from a given parameter.

The significance of the colour code is:

Black ➪ *N'va*	Red-➪ y''_{max}	Lime-➪ Jerk	Blue -➪ θ'_{max}
The vertical lines are averages			

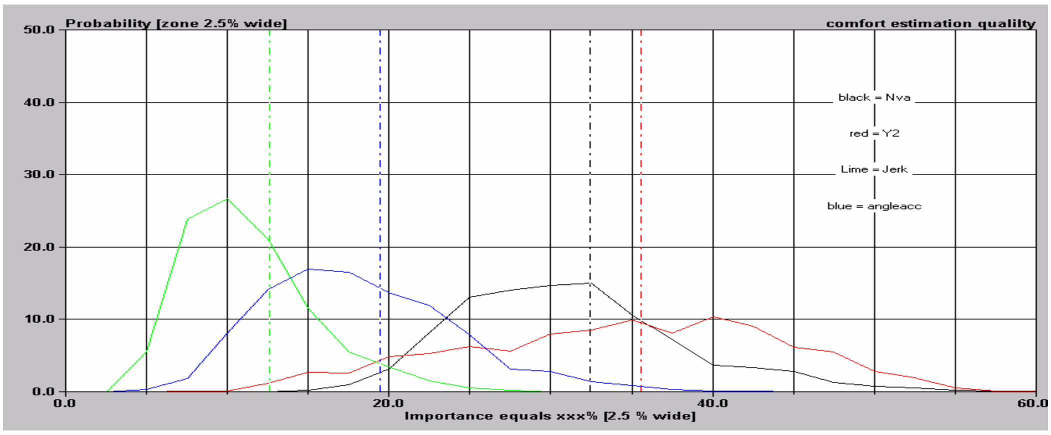


Figure 11-8 Contributions of individual parameters to the comfort index.

Comments

– Jerk and roll acceleration are clearly non-symmetrical distributions.
– The height of the curves is also influenced by the width of the histogram at the origin of this figure; therefore a cumulative distribution is more objective.

Cumulative probability functions for parameters' contribution.

This figure shows the probability of having a contribution of higher than (1-xxx)% to the total result from a given parameter.

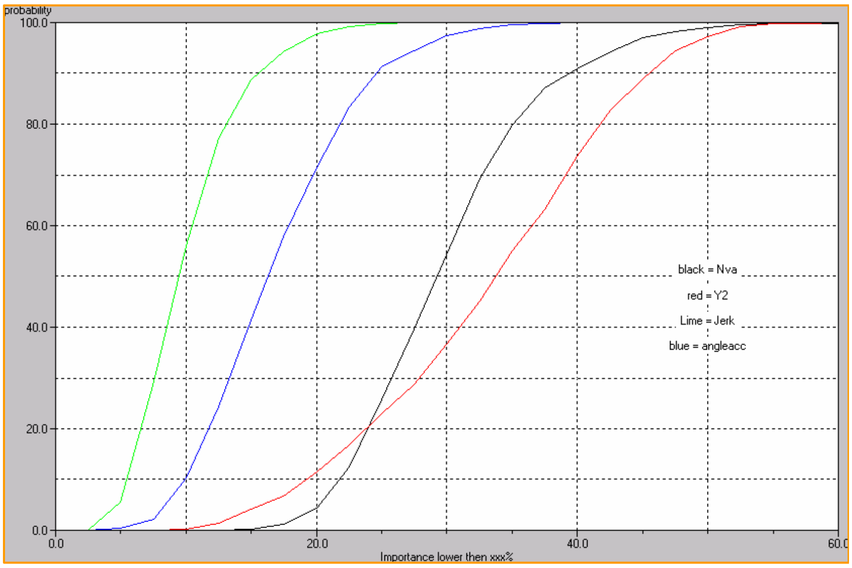


Figure 11-9 Cumulative distribution of parameters' contributions.

Colour code:

Black ➪ $N'va$ Red-➪ y''_{max} Lime-➪ Jerk Blue -➪ θ''_{max}

Some characteristic data points of the figure above are given in the table below:

Table 11-20 *Characteristic data of cumulative contribution of parameters.*

Prob	*Nva*	*Y"*	Jerk	*θ"*
10	22,5	20	7,5	10
20	25	25	10	12,5
30	27,5	30	12,5	15
40	30	32,5	15	17,5
50	32,5	35	17,5	20
60	35	37,5	20	22,5
70	37,5	40	22,5	25
80	40	42,5	25	27,5
90	42,5	47,5	27,5	30

Conclusion

This means that there are 20% of occasions where *N'va* has an participation of more than 40% in the discomfort, but also that there are 20% of occasions where θ" has a participation of at least 27.5 % in the building of discomfort.

So after all the angular acceleration seems to be more important than jerk
In a significant number of cases, roll acceleration is relatively important.

11.1.14 Estimation of group effect, knowing the regression model

In this chapter, data are not weighted to the number of participants in a group.

This explains small difference in coefficients. This restriction does not fundamentally modify the conclusion, which we believe to be valid.

Theory

The test used 8 different groups in 5 positions in the test train. The groups changed positions between test runs, but the composition of each group remained almost constant.

Because of the large differences between people's opinions, it is quite possible that the average votes of the groups differ because of personal preferences, and in this way corrupt the analysis.

If the test possesses enough data, it is possible to verify the inner distances between groups with the help of a technique called analysis of covariance.

The basis of the test is to calculate the variance of the dependent variable *Y*.

We consider:

1. The total variance. This is the variance of *Y* if no regression exists. *Y0*
2. The residual variance, this is the variance if a model x is applied, *Yr*[Model *x*]
3. The explained variance under model *x* *Yex*[model *x*]
4. *Yex*[model *x*] =*Y0*-*Yr*[model *x*]

In the analysis of variance we always consider two models. A model 1, where all possible parameters [*p* parameters] are included in the regression and a model 0 where a reduced set of parameters remain [*q* parameters are considered to be zero].

$$F = Yr\frac{[Model0] - Yr[Model1]}{Yr[Model1]} \times \frac{n-p}{q}$$

With those variances it is also possible to calculate the correlation

$$\rho^2 = Yr\frac{[Model1]}{[Model0]}$$

n is the total number of observations
p is the number of parameters in the complete regression
q is the number of parameters considered as zero in the reduced regression.

The probability of $F_{q,\, n-q}$ can be calculated, or read in tables.

In general, each regression consists of a constant term and a number of coefficients.

As a basic hypothesis we start from the supposition that the average of each group has identical coefficients but a different constant term.

The test will attempt to verify that individual constant terms can be considered as simultaneously zero.

A is the constant term if no distinction between groups has been made, we calculate for each group a correction term A-A_i where i is the group number.

The coefficients in the regression are calculated for

$$N'_{VA} \qquad \ddot{Y}_{\max 0.1} \qquad \dddot{Y}_{\max 0.1} \qquad \theta'_{\max 0.1}$$

We test then the hypothesis that the distinction between the groups can be considered as zero.

Application

All models are based on the complete collection of data for comfort in transition curves, for which *N'va* >0 and Votes >0. The number of experimental records is not weighted to the number of people in each group.

Full model [1]

Table 11-21 *Full model for estimation of group effect.*

	Reference	Value	Degrees of freedom	Degrees of freedom	Probability all parameters are equal to zero
F	1	78,0398	11	1087	0
Y0	2	816,7674			
***Yr* [model 1]**	3	456,3632			

Y0 (2) is the variance of the values *Y* if all coefficients are simultaneously zero.
Yr (3) is the remaining variance of the values *Y* when the regression is taken into account.

The difference (2)–(3) is the explained regression.

The probability that all coefficients are zero is judged by (1) the coefficient of Fischer-Snedecor, in this case with 11 and 1087 degrees of freedom. This probability is zero.

Table 11-22 *Difference in voting between the different groups.*

	Correction
G	0,2276
H	0,2155
E	-0,1043
F	-0,1125
D	-0,2968
A	-0,1851
B	0,1020
C	0,1538
SUM	0,0000

The calculation suggests following corrections (Comfort evaluation units)
note: Sum=0 because sum of all coefficients needs to be zero, the average value is not changed.

Reduced model

Alternative hypothesis: All correction coefficients are zero (no group effect).

Table 11-23 *Model with no group effect.*

F	179,4242	4	1094	1
Y0	816,7674			
***Yr* [model 2]**	493,2081			

Comparison between two hypotheses:

The probability that F=12.5 with 7 and 1087 degrees is a random value is smaller than 0.03%, so we have to accept that indeed there is a difference in voting between groups (not all correction coefficients are simultaneously zero).

The correlation factor is also reduced by 0.03 %.

However the estimated corrections are small.

Table 11-24 *Comparison between the two models with and without group effects.*

F	12,53715
Prob *F* >0	0,999752
df1	7
df2	1087

Conclusion

In spite of the positive test but taken into account that corrections are relatively small we advise not to take the corrections into account in further study.

11.1.15 Estimation of the residual influence of the position in the vehicle

This question is solved by an identical method.

Full model

Table 11-25 *Full model for estimation of effect of positions.*

Reference	Value	Degrees of freedom	Degrees of freedom	Probability all parameters are equal to zero
F	93,47005	8	1090	0
Y0	816,7674			
***Yr* [model 3]**	484,4355			

Estimated corrections

Table 11-26 *Difference in voting of the differens position.*

	Value
Rac1	0,1106
BB1	-0,1688
BBm	0,0510
BB2	0,0184
Bac1	-0,0112
Sum	0,0

Reduced regression

Table 11-27 *Reduced model with no influence of postions.*

F	179,4242	4	1094	1
Y0	816,7674			
***Yr* [model 4]**	493,2081			

Comparison between two hypotheses:

Table 11-28 *Comparison of the two models with and without influence of position.*

F	4,934666
Prob *F*>0	0,996841
df1	4
df2	1090

Conclusion

First conclusion

The result of the investigation is positive, position corrections are not zero, but their absolute value is very small, so that in practice it has no sense to take the position into account.

Second conclusion
This also proves that the regression that has been found is sufficiently good to take the different conditions in each of the different positions into account.

11.1.16 Linear estimations of the test subjects

Problem

If we plot the experimental votes (Y axis) against the estimated votes (X-axis) the figure suggests that at low level, the evaluation formula is too severe but at higher level under-estimates the discomfort, see for example Figure 11-7 or Figure 11-10.

At first visual inspection, the above sentence seems correct.

Study method

After sorting the matrix [estimated Votes, measured Votes] with respect to the estimated votes, we draw on the graph the moving average of the measured votes. The average was taken over 20 votes.

Conclusion

No non-linearity can be observed.

Any tentative suggestion to use a non-linear model to improve correlation was useless.

COLOUR CODE:

Group number	Colour	Group number	Color
1	red	5	black
2	fuchsia	6	lime
3	green	7	aqua
4	blue	8	purple

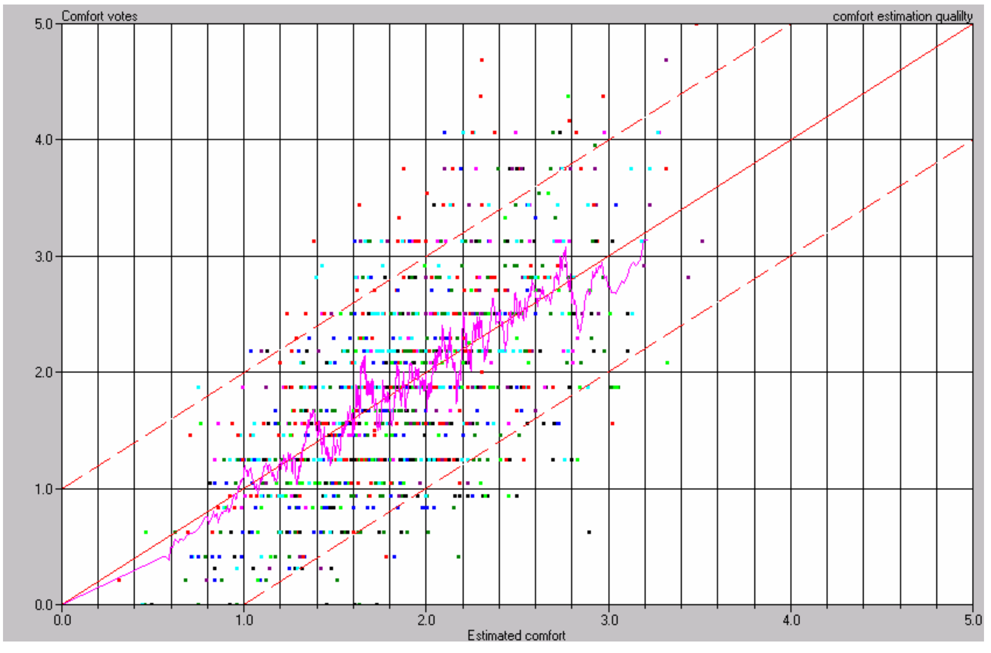


Figure 11-10 *Estimated comfort versus comfort votes with added moving average of 20 votes.*

The fuchsia line is the average group vote for 20 votes. This average line oscillates around the centreline. The behaviour is approx linear.

Study by histogram

Figure 11-11 gives an impression of the spread of the estimated votes for a given real vote.

For example, if all real votes equal to about 1.25 comfort units are grouped together then the associated estimations range from 0.5 to 2.75 comfort units with a maximum in the class 1.5 comfort units.

The same comment applies to the real votes in classes of 0.25 and 3 comfort units.

This corresponds with horizontal slices in Figure 11-10. The width of the class in the procedure = 0.25 comfort units. The estimated values are approximately symmetric around observed values.

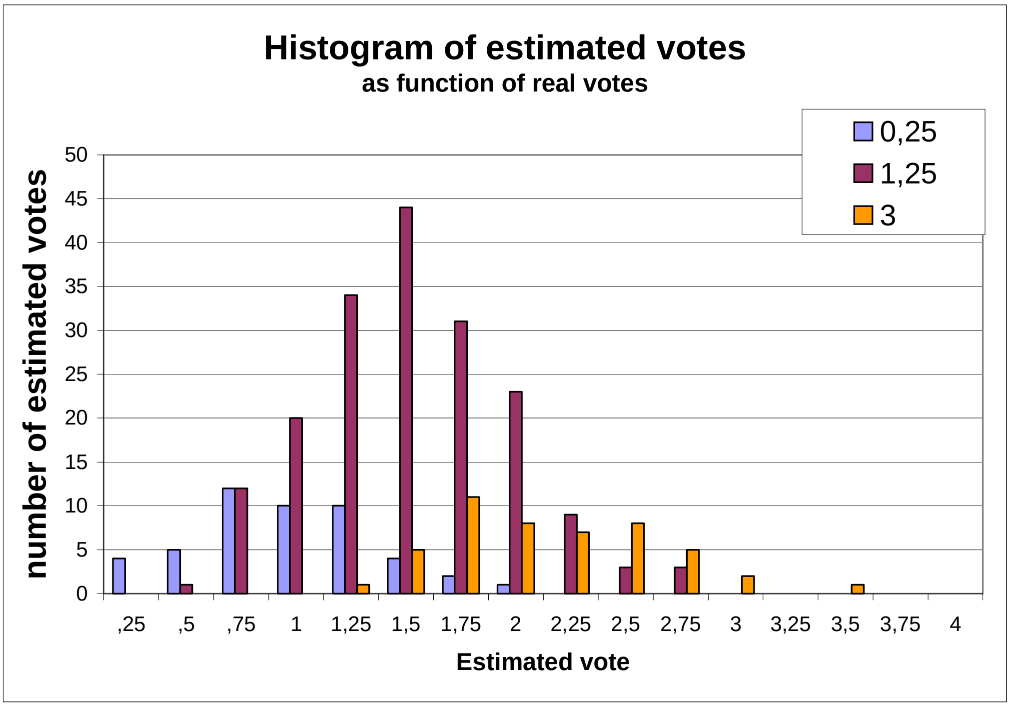


Figure 11-11 *Estimated votes for the three zones of recorded votes.*

Figure 11-11 is a histogram of the real votes for a choice of estimated votes. As could be expected from Figure 11-12 the spread of the real votes round a given estimated vote is significantly broader.

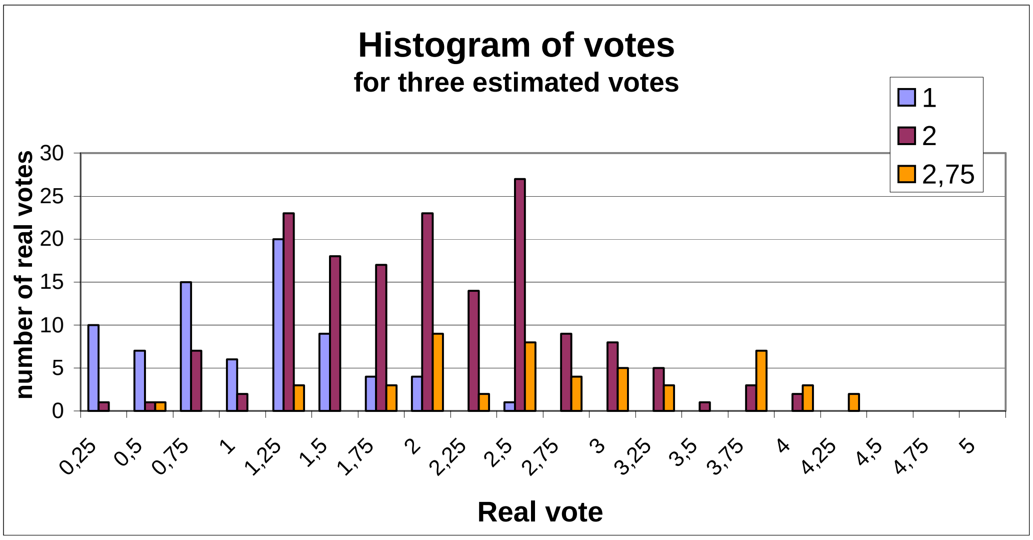


Figure 11-12 *Real votes for three zones of estimated votes. Here 1, 2 and 2.75 are the abscisses of the vertical slices in the data figure.*

11.1.17 Study of the errors: Measured-Estimation

A histogram of the distances between real and estimated votes gives following result.

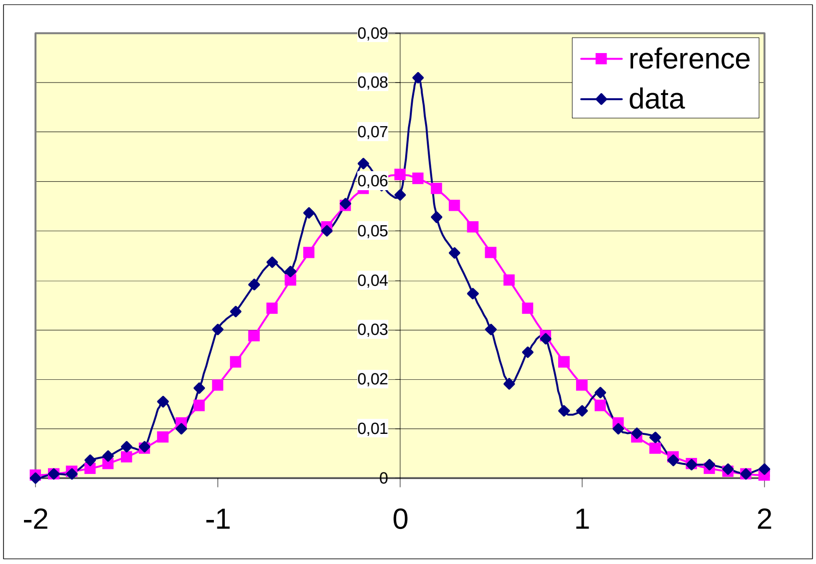


Figure 11-13 *Comparison between the experimental distribution and the normal distribution.*

The fuchsia curve is the normal distribution with an average of "0" and a standard deviation of 0.65 comfort units.

Taking into account that the estimation is done for a group of on average 5 persons we need an average of 0.20 for a standard deviation equal to 0.1 comfort unit.

The average of 35 persons gives a standard error of about 0.25 comfort units.

11.1.18 Conclusions on comfort in curve transitions

The best representation of the comfort in curve transitions is given by the expression

$$\text{Comfort Note} = 0.38*\, N'_{VA} + 0.64*\, \ddot{y}_{0.1\max} + 0.15*\, \dddot{y}_{0.1\max} + 0.032*\, \ddot{\theta}_{0.1\max} \qquad [11.1]$$

This uses parameters that are measured in the train, and with the relatively short averaging interval, are affected as much by the dynamic response of the train in the transition, as they are by the track geometry.

An alternative formulation is also proposed, which is considered to be more useful for track engineers when assessing the design geometry of a transition curve.

$$\text{Comfort Note} = 0.79*\, \ddot{y}_{1.0\max} + 0.24*\, \dddot{y}_{1.0\max} + 0.13*\, \dot{\theta}_{1.0\max} + 0.48 \qquad [11.2]$$

Although still using parameters measured in the vehicle, the use of a longer 1.0-second averaging interval and elimination of the comfort parameter N'_{VA} means that the parameters in the equation can be more directly related to the design track geometry. However, there exits a high correlation between lateral acceleration and jerk when the averaging time is 1s.

11.2 Analysis of Circular curves

11.2.1 Test Conditions

Test results for all four tilt conditions (80%, 60%, 40% and 0%) were combined into a single dataset. Both directions of running were included, giving a total of nine test runs after one of the 80% runs was repeated.

Each test run included seven (Firenze to Arezzo) or eight (Arezzo to Firenze) curved track test sites, chosen to give differing levels of non-compensated acceleration. In some runs not all sites were usable due to problems with instrumentation or train speeds.

Also included in the analysis dataset were the results from two straight track test sites on each test run. Straight track can be considered as a special case of a curve with zero lateral acceleration.

At each test site, votes and acceleration measurements were available for passengers at five different positions in the train. The votes for each group of passengers were averaged, and the average group vote used in regressions against the measured parameters for that group's location.

The groups at different positions in the train included four, six or eight passengers. In the regression analysis, the average vote for the whole group was used to help to improve the correlation of the results. However, to give the correct weight to each group according to its size, the results for groups of four were included twice in the regression, results for groups of six were included three times and results for groups of eight were included four times.

The combination of test runs, test sites and passenger locations gave a total of exactly 400 separate observations. After weighting, 1281 observations were input to the regressions.

11.2.2 Parameters

Four parameters were measured on curves and straight track – $\ddot{y}_m$, $\ddot{y}_p$, N'_{VA}, and P_{DE}.

$\ddot{y}_m$ and $\ddot{y}_p$ are the mean level and the peak-to-peak variation of acceleration in the test zone, measured according to the specification in Appendix N of ENV12299:1999.

N'_{VA} is a measure of the local ride comfort, being based on the same combination of vertical lateral and longitudinal accelerations as the established N_{VA} index, but applied locally to the test zone. All the components of N'_{VA} are subject to a band-pass filter, and so cannot include any influence from the mean level of acceleration. Therefore parameter N'_{VA} is independent of parameter $\ddot{y}_m$. However, as parameters N'_{VA} and $\ddot{y}_p$ are both dependent on dynamic values of acceleration, some relationship between them might be expected.

P_{DE} is not an independent variable, but is a comfort index derived from $\ddot{y}_m$ and $\ddot{y}_p$ according to the formula:

$$P_{DE} = 8.46 \cdot \ddot{y}_p + 13.05 \cdot \ddot{y}_m - 21.7$$

11.2.3 Scaling of votes

The N'_{VA} parameter is derived on a scale from 0 to 5. However, in the current test, the votes were based on push buttons scaling from 1 to 5. The votes from the current test were converted to the same scale as the N'_{VA} parameter, by the formula

Scaled vote = 1.25 * (measured vote – 1)

11.2.4 Examination of data

Before undertaking multiple regression analysis, it is advisable to make a visual examination of the data, looking at relationships between the parameters and votes, and look for any relationships between parameters.

Figure 11-14 shows the scaled votes (averaged for each position) plotted against the values of N'_{VA} and P_{DE} in the form of scatter plots. In each case the best-fit line from a single-parameter regression is also shown. Data from the curved and straight sections have been shown in different colours. Both of these measures are intended to be measures of ride quality, so that some correlation between them and the votes should be found. In fact the correlation between the votes and N'_{VA} is only 0.289, while the correlation with P_{DE} is a more respectable 0.553.

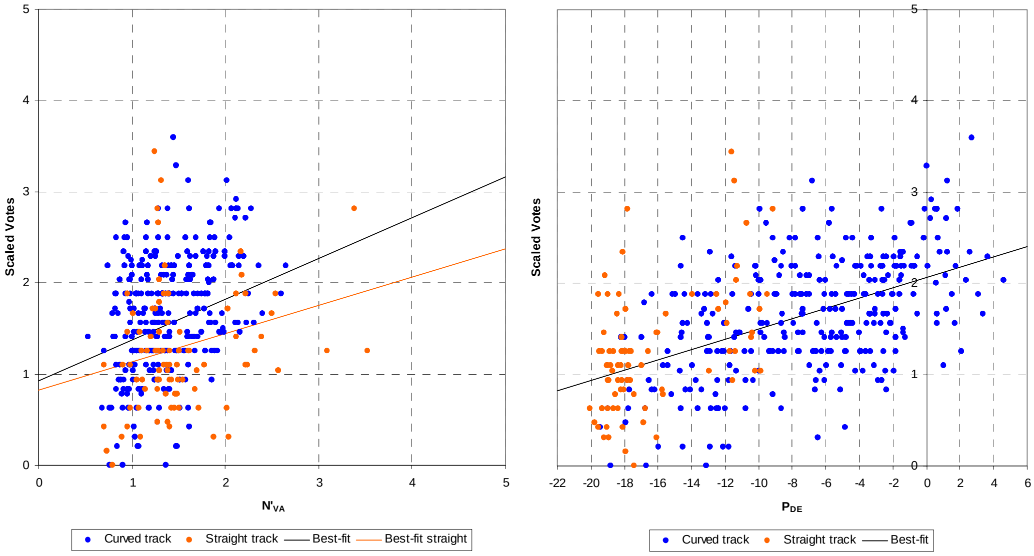


***Figure 11-14** Scatter plots – scaled votes against N'_{VA} and P_{DE}.*

As N_{VA} is the recommended ride measure for straight track, there should be a 1:1 correspondence between the scaled straight track votes and the N'_{VA} parameter. In fact the straight track votes show a very poor correlation with N'_{VA} of just 0.196, and the best-fit line for the straight track alone has a low slope and a high offset. This level of agreement is disappointing.

Figure 11-15 shows the relationship between the scaled votes and the individual components of P_{DE}, $\ddot{y}_m$ and $\ddot{y}_p$. The correlation between the votes with $\ddot{y}_m$ is 0.479, and with $\ddot{y}_p$ is 0.272.

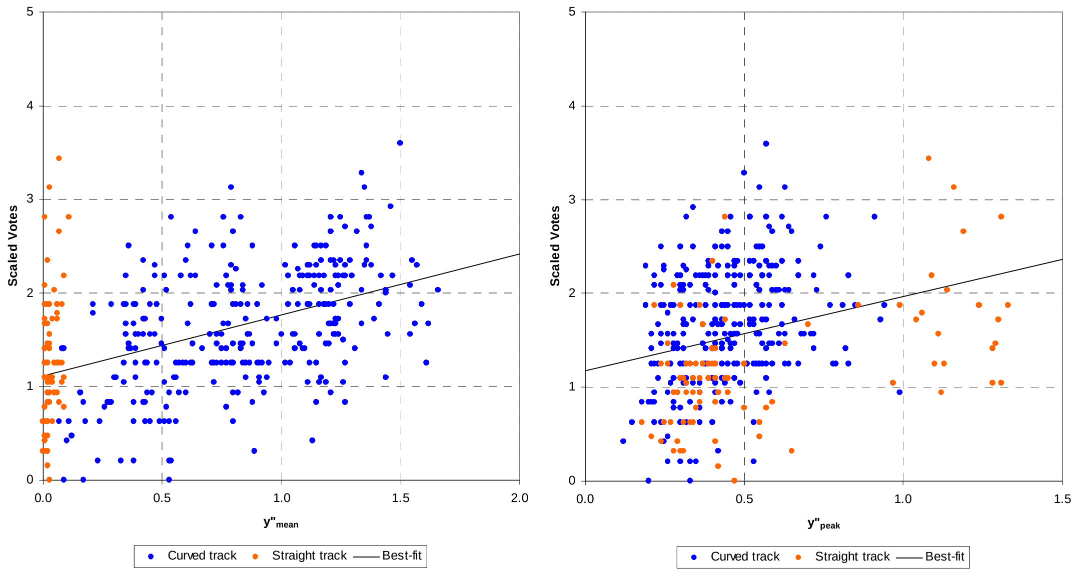


***Figure 11-15** Scatter plots – scaled votes and lateral acceleration parameters.*

There are some observations from the straight track sites which have much higher values of $\ddot{y}_p$ and N'_{VA} than any of the curved track observations. The high $\ddot{y}_p$ values are associated with straight ST1 in the direction from Firenze to Arezzo, while the high N'_{VA} values come from straight ST2 in the same direction. The high values of $\ddot{y}_p$ tend to have correspondingly higher votes, whereas the high values of N'_{VA} do not. This is one reason why the correlation between the votes and N'_{VA} on the straight track sections is so poor.

11.2.5 Relationship between parameters

As well as understanding the relationships of the measured parameters to the recorded votes, it is also important to understand the relationships of the parameters with each other. If two parameters are strongly correlated with each other, then including both in the same multiple regression will give invalid results.

The P_{DE} parameter is derived directly from the acceleration parameters used in this study, so it can only be used in a regression with N'_{VA}, and not with any of the acceleration parameters.

Figure 11-16 shows N'_{VA} plotted against P_{DE} and $\ddot{y}_p$. Against P_{DE} the best-fit line is almost horizontal, and the correlation from a single-parameter regression is just 0.041. Against $\ddot{y}_p$ there is a slight correlation, with a coefficient of 0.122. The abnormally high values of N'_{VA} or $\ddot{y}_p$ in some of the straight track tests can be clearly seen, and inevitably these must distort the data.

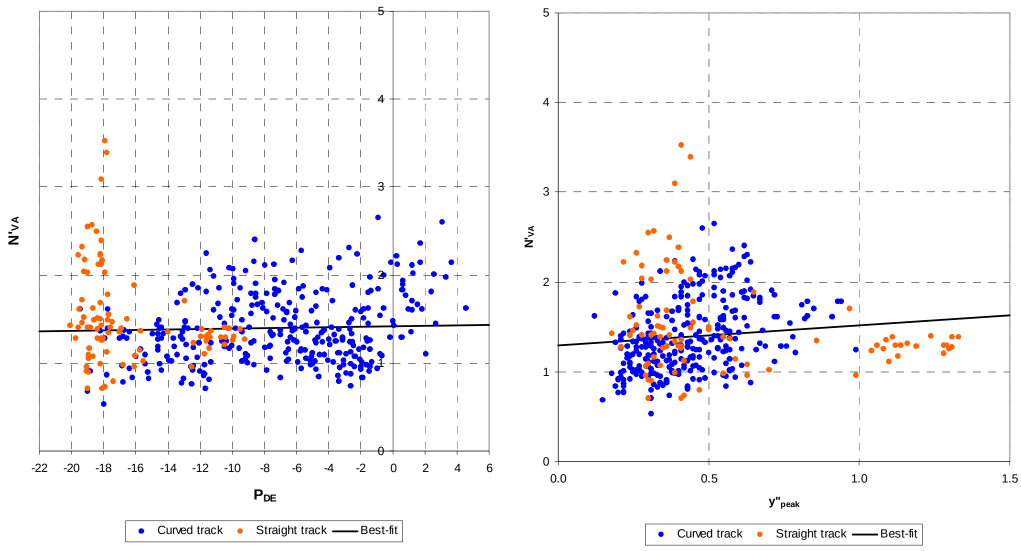


Figure 11-16 *Scatter plots – N'VA against PDE and* $\ddot{\mathbf{y}}_{\mathbf{p}}$.

Figure 11-17 shows N'_{VA} and $\ddot{y}_p$ plotted against $\ddot{y}_m$. There is no correlation between N'_{VA} and $\ddot{y}_m$, with a coefficient of 0.004, and the best-fit line is horizontal. There is almost no correlation between $\ddot{y}_p$ and $\ddot{y}_m$, with a coefficient of 0.092, and the best-fit line has a negative slope. This could be due to distortion from the high values of $\ddot{y}_p$ in some of the straight track tests.

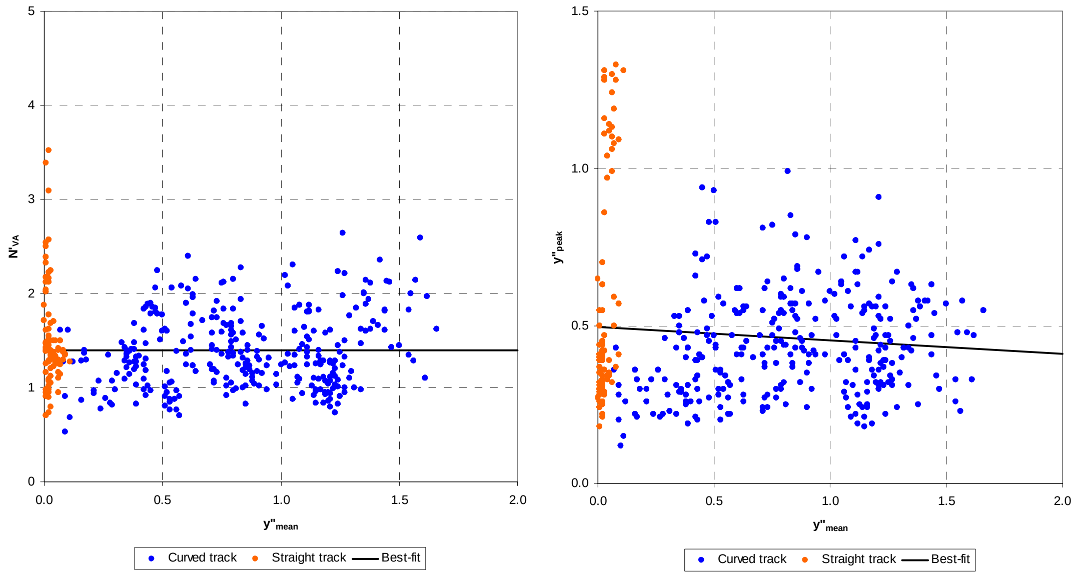


Figure 11-17 *Scatter plot – N'va and* $\ddot{\mathbf{y}}_{\mathbf{p}}$ *against* $\ddot{\mathbf{y}}_{\mathbf{m}}$.

11.2.6 Regression analysis

The results for the single parameter regressions already shown in Figures 11-14 and 11-15 are summarised in Table 11-29.

Table 11-29 *Single parameter regressions.*

Parameter	Equation	Correlation
N'_{VA}	Scaled Vote = 0.45* N'_{VA} + 0.92	0.289
P_{DE}	Scaled Vote = 0.056* P_{DE} + 2.06	0.553
$\ddot{y}_m$	Scaled Vote = 0.65* $\ddot{y}_m$ + 1.12	0.479
$\ddot{y}_p$	Scaled Vote = 0.79* $\ddot{y}_p$ + 1.18	0.272

The best correlation is found from the P_{DE} parameter, and the next best correlation from the mean acceleration $\ddot{y}_m$, which is a component of P_{DE}. The correlation with N'_{VA} is poor, and the coefficient surprisingly low - if the votes were to follow the pattern established in the earlier work of ERRI B153 then the coefficient for N'_{VA} should be 1.0.

Two two-parameter regressions were tried, combining N'_{VA} with P_{DE} and $\ddot{y}_m$, with the results shown in Table 11-30.

Table 11-30 *Two-parameter regressions.*

Object: Circular curves and Straight Track (all data)				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.613	385.4	1281
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.412	12.1	+37%
	P_{DE}	0.055	24.5	-26%
	Intercept	1.475	27.0	+95%

Object: Circular curves and Straight Track (all data)				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.559	298.7	1281
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.444	12.4	40%
	$\ddot{y}_m$	0.648	20.6	26%
	Intercept	0.499	8.9	95%

Including N'_{VA} as well as P_{DE} significantly improves the correlation compared to P_{DE} alone. However, replacing P_{DE} by $\ddot{y}_m$ gives a poorer correlation.

The *t*-value is a measure of the significance of each parameter in the regression. In these regressions, all of the parameters have quite high *t*-values, and cannot be ignored.

The column showing typical contribution for each parameter shows the result of multiplying the average value of the parameter by the coefficient. This gives an indication of the contribution of each term in the regression equation to a typical predicted vote.

The quality of the regressions can be seen in a plot of the predicted against measured votes in Figure 11-18.

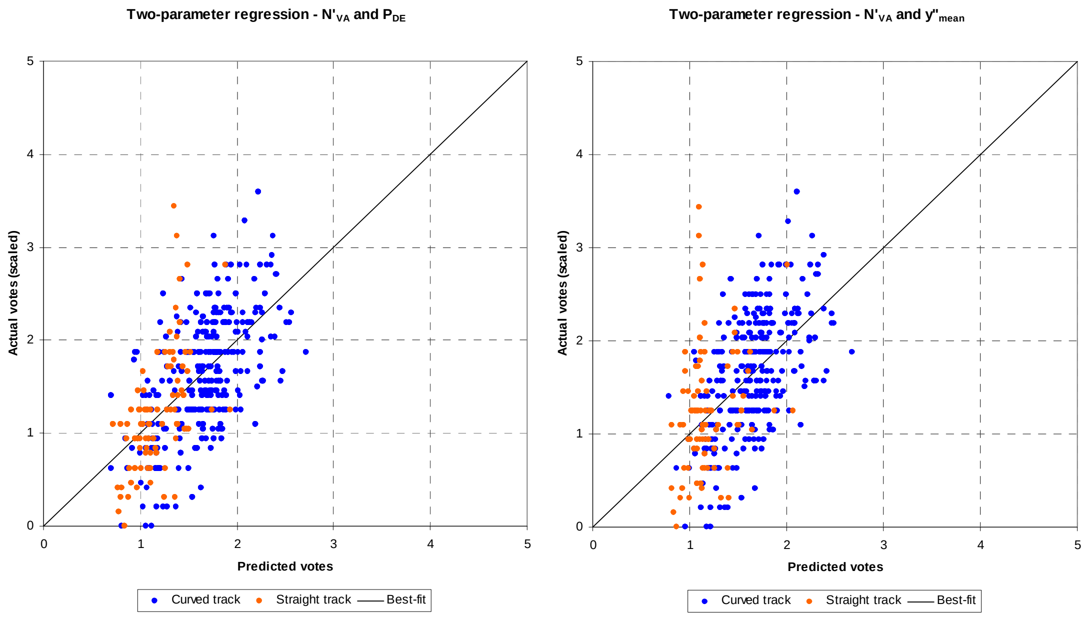


Figure 11-18 *Quality of regression – two-parameter regressions.*

A three-parameter regression was tried, including N'_{VA} and both components of P_{DE}, $\ddot{y}_m$ and $\ddot{y}_p$, with the results shown in Table 11-31.

Table 11-31 *Three-parameter regression.*

Object: Circular curves and Straight Track (all data)				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.627	275.3	1281
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.389	11.5	35%
	$\ddot{y}_m$	0.684	23.0	26%
	$\ddot{y}_p$	0.830	13.8	25%
	Intercept	0.163	2.8	10%

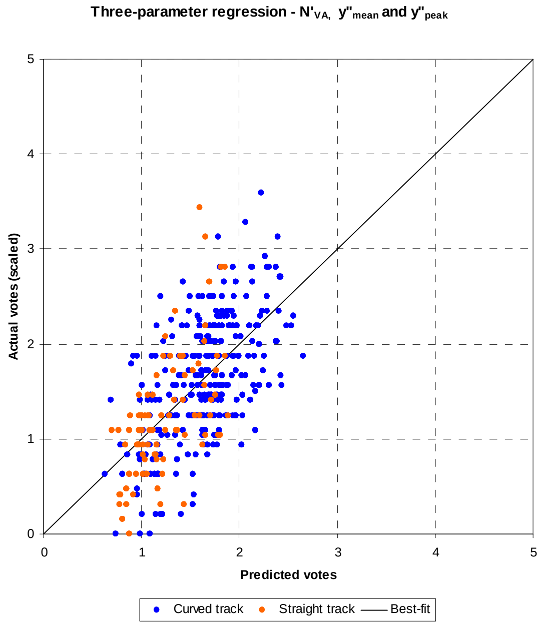


Figure 11-19 *Quality of regression – three-parameter regression.*

This regression gives the best correlation, but it is only slightly better than obtained using N'_{VA} and P_{DE}. The quality of the regression is shown in Figure 11-19.

11.2.7 Regressions with Reduced Dataset

As was discussed in the section on "Examination of Data" above, two of the straight track sections had abnormally high values of N'_{VA} or $\ddot{y}_p$, which may have distorted the results. The multiple regression analysis has been repeated without the data from those two sections.

The two-parameter regressions gave the results shown in Table 11-32.

Table 11-32 Two-parameter regressions – reduced dataset.

Object: Circular curves and Straight Track (reduced data)				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.650	408.8	1121
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.405	9.9	+35%
	P_{DE}	0.058	23.4	-31%
	Intercept	1.480	22.5	+95%

Object: Circular curves and Straight Track (reduced data)				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.639	384.8	1121
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.483	11.8	43%
	$\ddot{y}_m$	0.777	22.5	37%
	Intercept	0.311	5.3	20%

Eliminating the two straight track sites has greatly improved the correlation – although the importance of the N'_{VA} parameter has been further reduced. The quality of the regressions is shown in Figure 11-20.

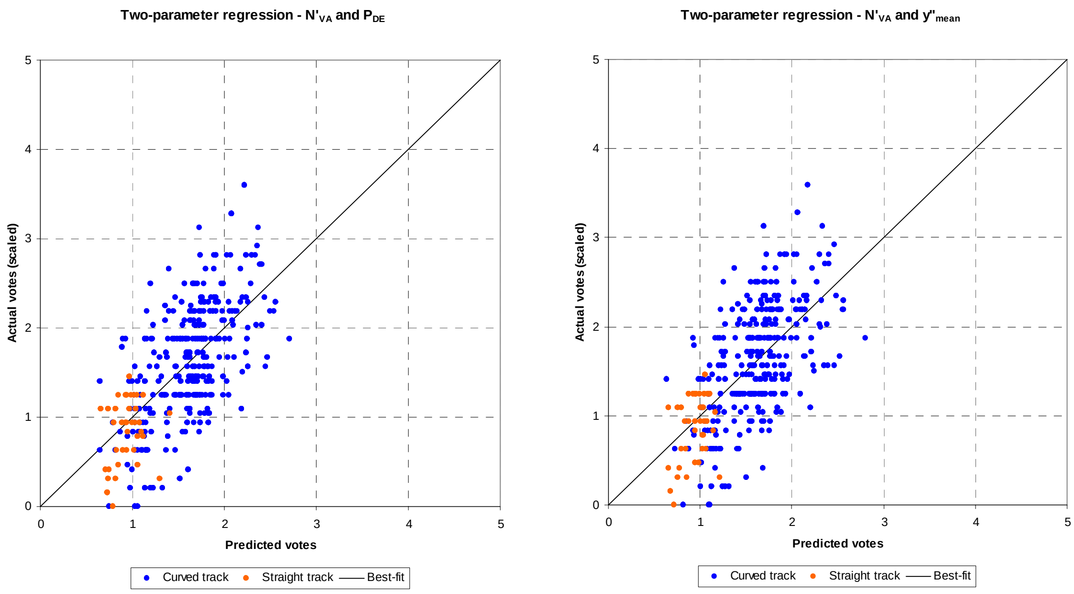


***Figure 11-20** Quality of regression – two-parameter regressions with reduced dataset.*

The three-parameter regression was repeated, as shown in Table 11-33.

Table 11-33 *Three-parameter regression – reduced dataset.*

Object: Circular curves and Straight Track (reduced dataset)				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.650	272.3	1121
	Probability	<0.1%	<0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.397	9.2	35%
	$\ddot{y}_m$	0.755	22.0	37%
	$\ddot{y}_p$	0.549	5.3	15%
	Intercept	0.205	3.3	13%

Note that this time the correlation is no better than is obtained in the two-parameter regression using N'_{VA} and P_{DE}. This suggests that the combination of $\ddot{y}_m$ and $\ddot{y}_p$ in the formula for P_{DE} must be close to optimum for the current data.

Finally, it will be seen that the value of the intercept in this equation is quite small, and the *t*-value suggests that it has a relatively low importance. It is desirable to have an equation that has a zero value for zero inputs, so the regression has been repeated forcing the intercept to zero, with the results shown in Table 11-24.

Table 11-34 *Zero-intercept three-parameter regression – reduced dataset.*

Object: Circular curves and Straight Track (all data)				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.645	266.1	1121
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.490	14.6	43%
	$\ddot{y}_m$	0.780	23.1	38%
	$\ddot{y}_p$	0.661	6.7	19%

The correlation is slightly reduced, but still very respectable.

The quality of the regression for the last two cases is shown in Figure 11-21.

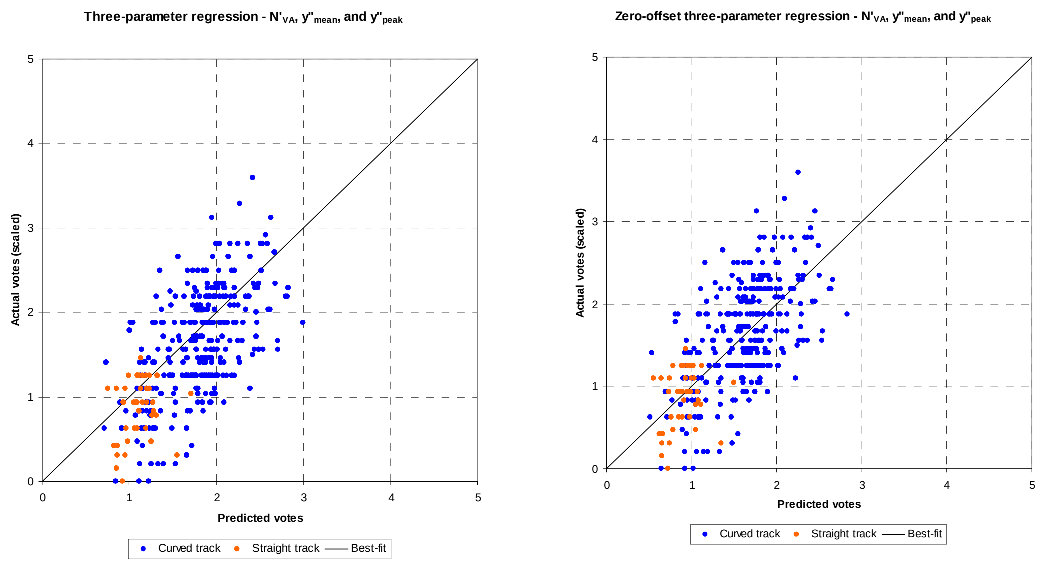


Figure 11-21 *Quality of regression – three-parameter regressions.*

11.2.8 Conclusion on comfort in circular curves

In a circular curve, it was expected that the passenger response would have been governed by the general ride quality (which can be measured by N'_{VA}) and by the quasi-static lateral acceleration (which is not included in N'_{VA}, and is measured by $\ddot{y}_m$).

The N'_{VA} measure and the peak-to-peak acceleration $\ddot{y}_p$ both include the effect of dynamic accelerations in the vehicle. However, there is very little correlation between them in the measured data, and both parameters are needed in the regression to achieve the best correlation. Clearly, the N'_{VA} measure alone is not sufficient to account for the dynamic accelerations.

Correlations are substantially improved by removing the two anomalous straight track sites, and it is recommended that the resulting data is to be preferred.

A two-parameter regression using P_{DE} and N'_{VA} gives the best correlation. However, as P_{DE} is mostly negative in the curves investigated, it seems preferable to use the results of the three-parameter regression, including parameters $\ddot{y}_m$, $\ddot{y}_p$ and N'_{VA}, which gives an almost equal correlation.

Forcing the intercept to zero gives only a slight loss of correlation, but has the benefit of giving a measure which has a zero value with no inputs. Thus the preferred relationship that emerges for the comfort in steady curves is

$$\text{Comfort Note} = 0.490 * N'_{VA} + 0.780 * \ddot{y}_m + 0.661 * \ddot{y}_p \qquad [11.3]$$

12 Evaluation of average comfort

12.1 Analysis of average comfort

12.1.1 Test Conditions

Test results for three tilt conditions (80%, 60% and 0% compensation) were combined into a single dataset for analysis. Both directions of running were included, giving a total of eight test runs (with two 80% runs in each direction).

At each test site, votes and acceleration measurements were available for passengers at five different positions in the train. The votes for each group of passengers were averaged, and the average group vote used in regressions against the measured parameters for that group's location.

The groups at different positions in the train included four, six or eight passengers. In the regression analysis, each group's votes were averaged to help to improve the correlation of the results. However, to give the correct weight to each group according to its size, results for groups of four were included twice in the regression, results for groups of six were included three times and results for groups of eight were included four times.

12.1.2 Parameters

The parameters that were selected for measurement were five individually measured parameters, and one derived parameter combining accelerations in different directions.

The five individual parameters that were measured were

- $\ddot{y}$ - the value of lateral acceleration
- $\dddot{y}$ - the rate of change of lateral acceleration (or jerk)
- $\dot{\theta}$ - the roll velocity
- $\ddot{y}_{MeanCEN}$ - Mean Lateral Acceleration, CEN rule
- $\ddot{y}_{PPCEN}$ - Peak to Peak Lateral Acceleration, CEN rule

The parameter derived from a combination of different acceleration measurements was

- N'_{VA}

N'_{VA} is a derived parameter representing the general ride comfort in the test zone. A comfort weighting filter is applied which eliminates low frequency effects including any influence of transition curves.

Each of these parameters was calculated for 60 5-second blocks in each 5-minute test zone, and then the 50th, 95th and 100th percentiles were used as inputs to the regression analysis.

In addition, the global value of parameter N_{VA} was calculated, being an overall value for each 5-minute test zone calculated according to UIC leaflet 513.

12.1.3 Scaling of votes

The N'_{VA} parameter is derived on a scale from 0 to 5. However, in the current test, the votes were based on push buttons scaling from 1 to 5. The votes from the current test were converted to the same scale as the N'_{VA} parameter, by the formula

Scaled vote = 1.25 * (measured vote – 1)

12.1.4 Examination of data

Before undertaking multiple regression analysis, it is advisable to make a visual examination of the data, looking at relationships between the parameters and votes, and looking for any relationships between parameters.

In this case, as a number of different percentiles of results were recorded, it was firstly necessary to decide which percentile group of each parameter would be used. The feasibility of using more than one percentile of each parameter in a multiple regression was also investigated. In order to be able to do this, it would be necessary for the percentiles not to display a strong correlation with one another. Therefore, two preliminary stages of examination were carried out to calculate the correlation coefficient of the different percentiles against the scaled votes, and to compare the different percentiles of each parameter against each other. These results are shown in Tables 12-1 and 12-2 respectively.

Table 12-1 *Correlation Coefficients – Parameters against Scaled Votes (percentiles).*

	50th percentile	95th percentile	100th percentile
$\ddot{y}$	**0.221**	0.157	0.207
$\dddot{y}$	**0.203**	0.118	0.187
$\dot{\theta}$	**0.344**	0.269	0.311
$\ddot{y}_{MeanCEN}$	0.165	0.155	**0.175**
$\ddot{y}_{PPCEN}$	0.326	0.330	**0.333**
N'_{VA}	**0.284**	0.205	0.157

	No percentile
N_{VA}	**0.214**

Table 12-2 *Correlation Coefficients – Different Percentiles.*

	50th vs 95th percentile	50th vs 100th percentile	95th vs 100th percentile
$\ddot{y}$	0.816	0.797	0.956
$\dddot{y}$	0.820	0.854	0.970
$\dot{\theta}$	0.830	0.590	0.702
$\ddot{y}_{MeanCEN}$	0.842	0.770	0.956
$\ddot{y}_{PPCEN}$	0.827	0.822	0.888
N'_{VA}	0.804	0.646	0.806

Table 12-2 shows that the correlations of different percentiles against each other for the same parameter are all high, therefore more than one percentile of each parameter will not be used for further analysis. Instead, the percentiles corresponding to the best correlation with votes will be used. These are shown in bold in Table 12-1, and equate to the 50th percentile for Lateral Acceleration, Roll Velocity, Lateral Jerk and N'_{VA}, and 100th percentile for the two CEN parameters of mean and peak to peak Lateral Acceleration.

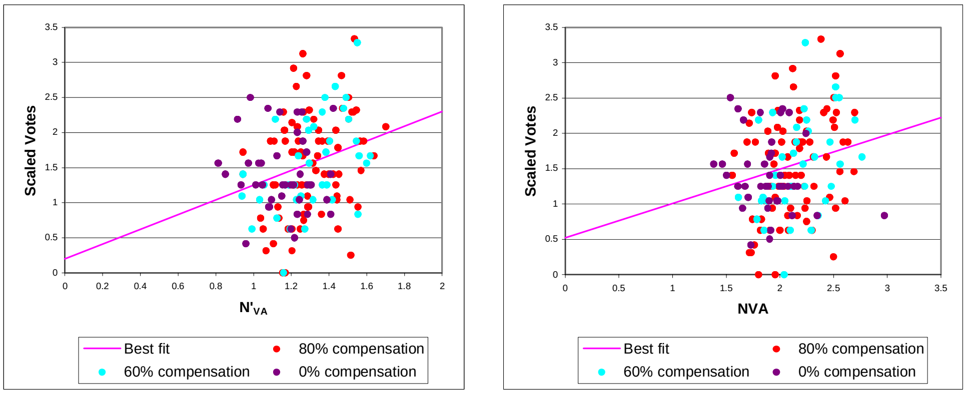


Figure 12-1 *Scatter plots –votes against N'_{VA} and N_{VA}.*

Figure 12-1 shows the scaled votes (averaged for each position) plotted against the values of the derived parameters N'_{VA} and N_{VA} in the form of scatter plots. Data for each tilt compensation level are differentiated by colour. The best-fit line from a single-parameter regression is also shown.

Both the derived measurements are intended to represent ride quality, so that some correlation with the recorded votes could be expected. In fact the correlation coefficients are 0.284 for N'_{VA} and 0.214 for N_{VA}, which are not as high as might have been expected.

12.1.5 Relationship between parameters

As well as understanding the relationships of the measured parameters to the recorded votes, it is also important to understand the relationships of the parameters with each other. If two parameters are strongly correlated with each other, then including both in the same multiple regression will give invalid results. Values for these calculations are shown in Table 12-3, using the best percentiles as identified in Table 12-1.

Table 12-3 *Correlation coefficients – parameters against each other.*

	$\ddot{y}$	$\dddot{y}$	$\dot{\theta}$	$\ddot{y}_{MeanCEN}$	$\ddot{y}_{PPCEN}$	N'_{VA}	N_{VA}
$\ddot{y}$		0.252	0.272	**0.768**	**0.522**	0.035	0.045
$\dddot{y}$			0.306	0.465	0.096	0.346	0.398
$\dot{\theta}$				0.198	0.494	**0.500**	0.382
$\ddot{y}_{MeanCEN}$					**0.507**	0.005	0.025
$\ddot{y}_{PPCEN}$						0.090	0.107
N'_{VA}							**0.818**
NVA							

In Table 12-3 correlations of 0.500 or more have been shown in bold, and indicate that where this occurs the two parameters should not be used together in a multiple regression analysis. As might have been expected there is strong correlation between Lateral Acceleration and the two CEN calculated values of Lateral Acceleration, as there is between the CEN parameters themselves. Therefore, only one of these three parameters will be used in any multiple regression analysis at any one time. There is also strong correlation between the N'_{VA} and N_{VA} parameters, which is also expected. Therefore, it was decided to only use the N_{VA} parameter in any regression analysis; this is the more correct parameter to use. There is also a marginally strong correlation between N'_{VA} and Roll Velocity, but as the N'_{VA} parameter will not be used, this has no impact on the multiple regression parameter choice.

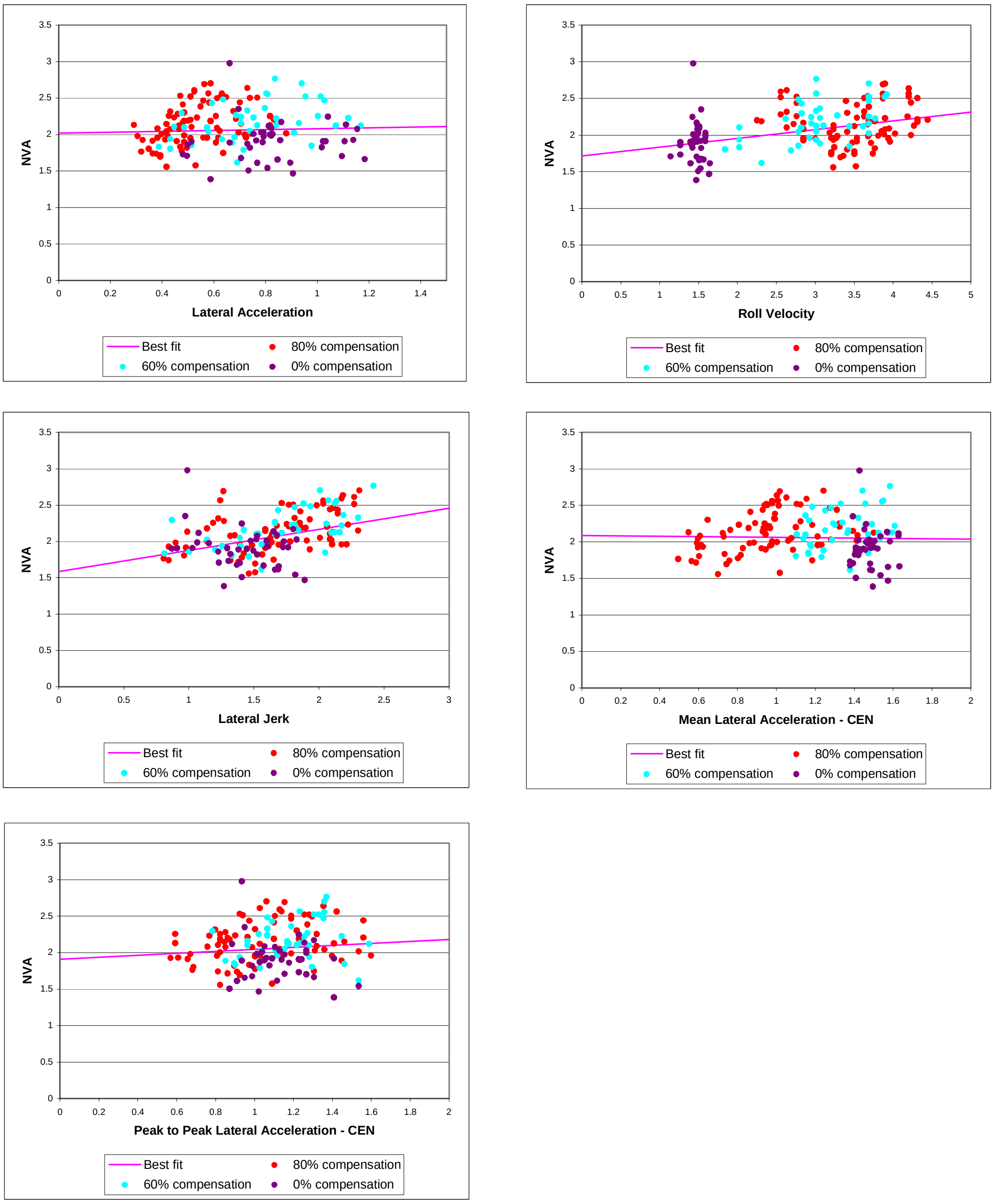


Figure 12-2 *Scatter plots – N_{VA} against individual parameters.*

Figure 12-2 shows N_{VA} plotted against the individual parameters (with the exception of N'_{VA}). It can be seen that there is a very low correlation between this parameter and any of the others. The actual values of correlation coefficient are displayed in Table 12-3.

Figure 12-3 shows scatter plots for lateral acceleration plotted against the CEN Lateral Acceleration parameters in order to demonstrate the much closer correlation seen between these parameters.

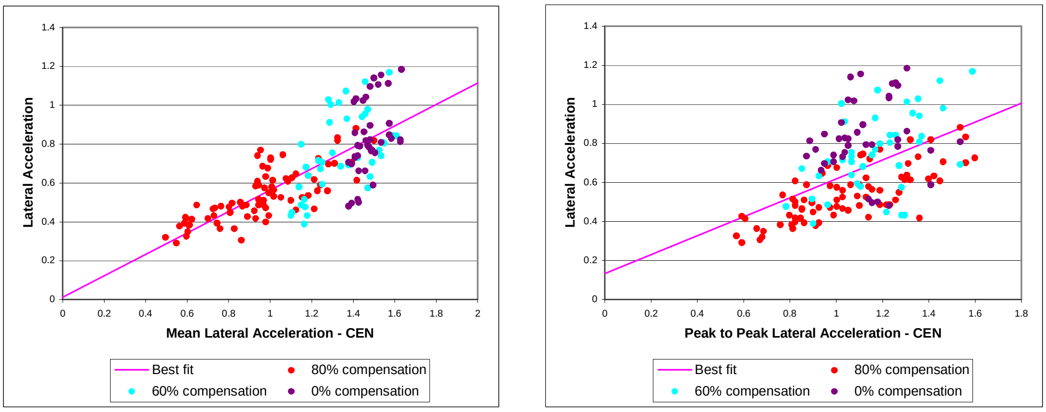


Figure 12-3 *Scatter Plots of Lateral Acceleration against Other Parameters.*

12.1.6 Regression analysis

None of the single parameter regression analyses showed a correlation of any individual parameter against the actual votes. Therefore, several multiple parameter regressions were tried to see if a combination of parameters would lead to higher levels of correlation. A selection of these that gave the highest values of correlation coefficient is given below in Table 12-4 to 12-7.

Table 12-4 *Multiple regression for Average Comfort, version 1.*

Object: Average Comfort 5 parameters with $\ddot{y}_{PPCEN}$				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.415	26.4	512
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N_{VA}	0.200	0.1	+27%
	$\dot{\theta}$	0.065	2.1	+12%
	$\ddot{y}$	0.287	3.3	+31%
	$\ddot{y}_{PPCEN}$	0.669	5.0	+49%
	Intercept	-0.285	-1.3	-19%

__Table 12-5__ Multiple regression for Average Comfort, version 2.

Object: Average Comfort with 5 parameters with $\ddot{y}_{mean}$				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.406	25.0	512
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N_{VA}	0.128	1.2	+26%
	$\ddot{y}$	0.622	4.4	+24%
	$\dot{\theta}$	0.113	3.4	+19%
	$\dddot{y}$	0.374	4.6	+36%
	Intercept	-0.095	-0.4	-5%

__Table 12-6__ Multiple regression for Average Comfort, version 3.

Object: Average Comfort 5 parameters using max values				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0,415	26,36839	512
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N_{VA}	0.126	1.2	
	$\ddot{y}$	0.655	6.1	
	$\dot{\theta}$	0.089	4.5	
	$\dddot{y}$	0.113	3.9	
	Intercept	-0.660	-2.7	

__Table 12-7__ Multiple regression for Average Comfort, version 4.

Object: Average Comfort using 4 parameters (without $\dot{\theta}$)				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.407	33.5	512
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N_{VA}	0.270	2.7	+37%
	$\dddot{y}$	0.320	3.7	+34%
	$\ddot{y}_{PPCEN}$	0.659	4.9	+48%
	Intercept	-0.284	-1.3	-19%

Correlations are much less than with the local comfort results. This may be due to the much smaller sample size in the average comfort analysis.

It was thought that it might be possible to improve the correlation through averaging of the raw data before carrying out the regression analysis. Therefore, an averaging method was used, whereby all results were placed in order of increasing votes, and averaged over five values at a time. This also meant that the number of points used in the regression analysis would be reduced by a factor of five.

Table 12-8 shows the results of repeating the chosen multiple regression after averaging.

Table 12-8 *Selection of Multiple Regressions After Use of Averaging Method.*

Object: Average Comfort – averaged data				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.514	8.79	103
	Probability	0.00000006	0.00000417	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N_{VA}	0.365	1.2	+44%
	$\ddot{y}$	0.765	2.1	+30%
	$\dot{\theta}$	0.109	1.2	+18%
	$\dddot{y}$	0.719	3.1	+69%
	Intercept	-1.22	-2.1	-71%

Although the averaged data gives significantly better correlation, the Fischer-Snedecor parameter (F-Value) is reduced. The probability that all parameters in the regression are zero has increased – suggesting that the averaged values in fact give a poorer quality regression.

Of the multiple regressions, the second of the regressions without averaging (with 0.406 correlation) was considered by the working group to be the most appropriate for further consideration. However, it can be seen that the value of the intercept is small, and it has a very small t-value associated with it. Thus, the regression was repeated, forcing the intercept to have a zero value, as shown in Table 12-9.

Table 12-9 *Multiple Regression with zero intercept.*

Object: Average Comfort				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.405	25.0	512
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N_{VA}	0.094	1.3	13%
	$\ddot{y}$	0.601	4.5	26%
	$\dot{\theta}$	0.111	3.4	21%
	$\dddot{y}$	0.371	4.5	40%

This is the preferred result to be used for assessing average comfort on curvaceous routes.

Table12-6 does give a slightly higher correlation, but, using maximum values, representing just 0.1 second from a time zone of 5 minutes, gives too high a risk of introducing erroneous values.

12.2 Discussion of the results

12.2.1 Preliminary Conclusion

The results of the analysis of average comfort are disappointing, as they show quite low correlation between the passenger comfort votes and any of the measured parameters, even after the use of a further averaging method. However, this may be explained by the relatively small sample of data that was examined.

The Fischer-Snedecor parameter (*F* Value) has also been listed in all results tables, which allows for testing the hypothesis that all regression coefficients in each analysis are zero against the proposed relationship. Despite the very small correlation values, the *F* coefficient remains acceptable.

The chosen relationship to represent the comfort on curvaceous routes is given by

$$\text{Comfort Note} = 0.094 * N_{VA} + 0.60 * \ddot{y} + 0.11 * \dot{\theta} + 0.37 * \dddot{y} \qquad [12.13]$$

where the lateral and roll parameters are the 50th percentile values, calculated according to the method given in Appendix 1.

12.2.2 General quality of the regression

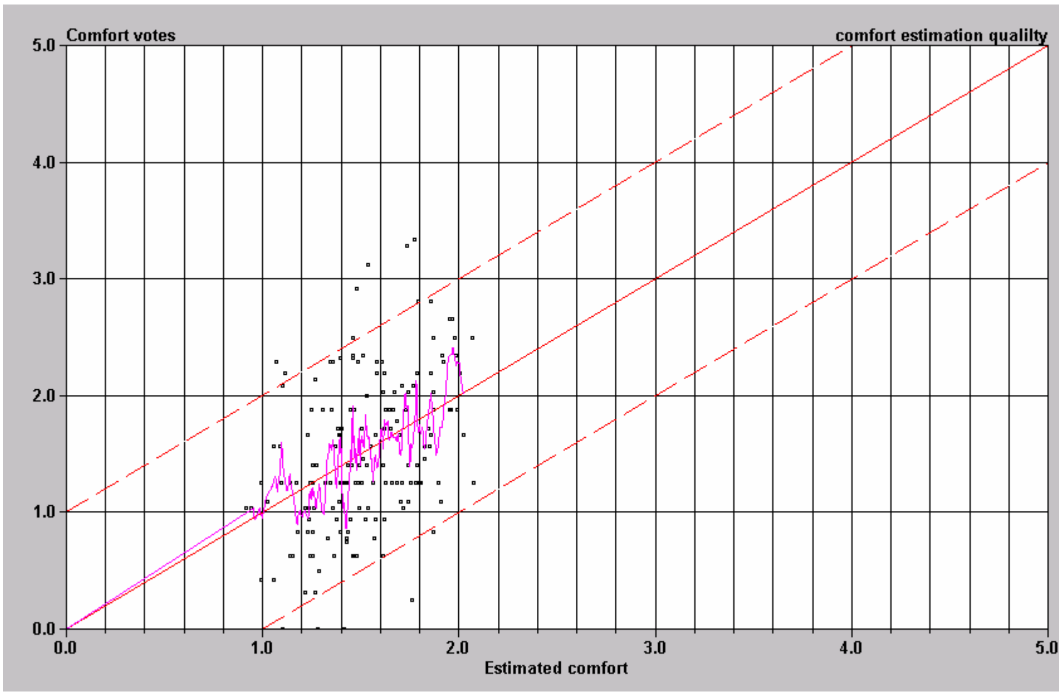


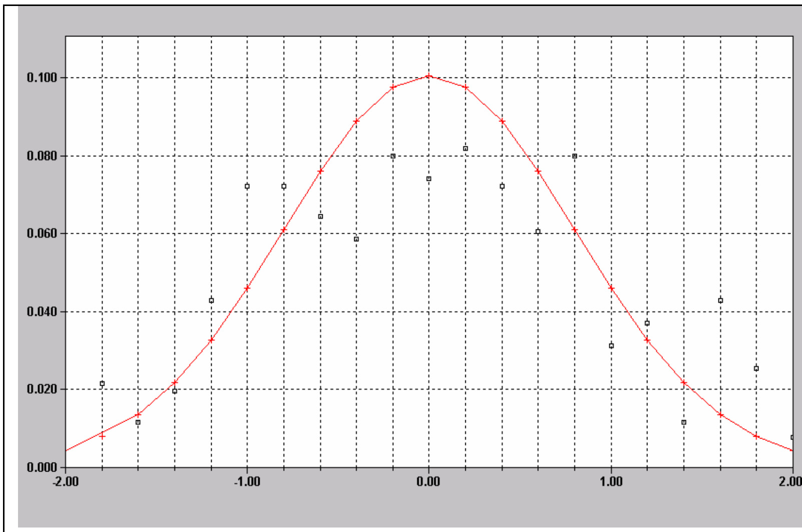
Figure 12-4 *Estimated comfort versus votes for average comfort and a curve for average of 20 votes.*

The figure above shows an identical picture as with for local comfort.

The scatter is large, but expected for this kind of investigation.

The average votes correspond very well with the estimation.

12.2.3 Spread of the errors



The spread of the errors is also very comparable with the local comfort.

The standard error of the spread is about 0.597 comfort units.

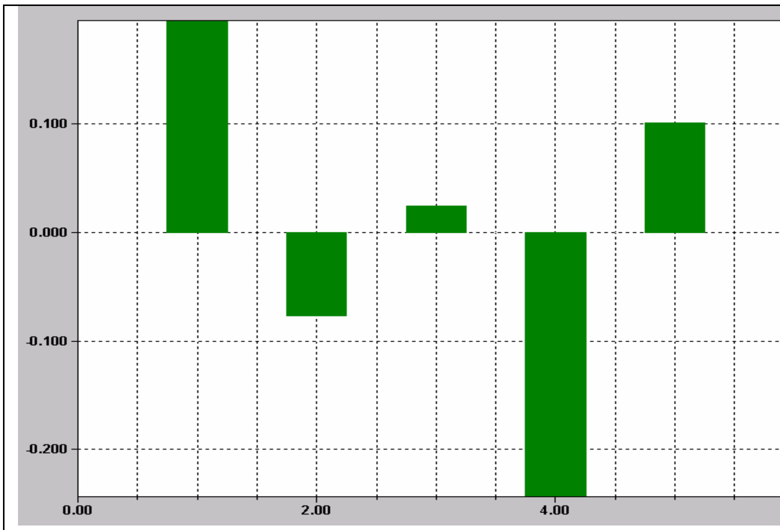
Figure 12-5 Spread of errors for estimation of average comfort.

Method of calculation

For each observation, the error is calculated.

These errors are normalised in spread by dividing by the square root of the variance.

12.2.4 Average error per place in train

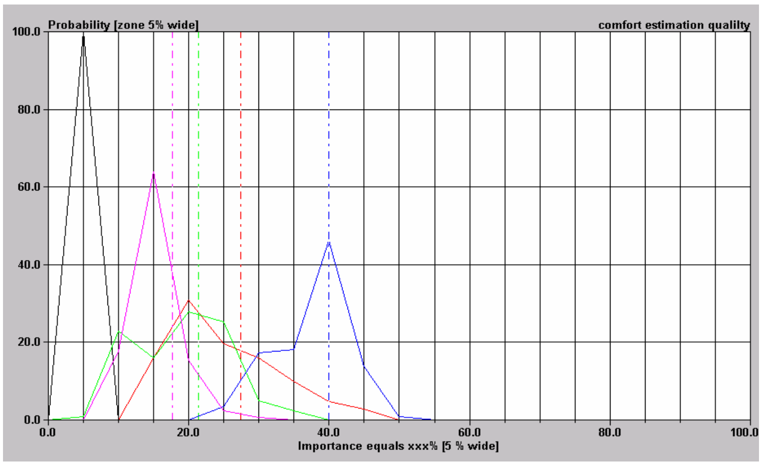


The average error per occupied position does not suggest a influence of the position in the train.

Positions from left to right:
LL
ML
MM
MT
TT

Figure 12-6 Spread of average error per position in the train.

12.2.5 Density of importance of each parameter

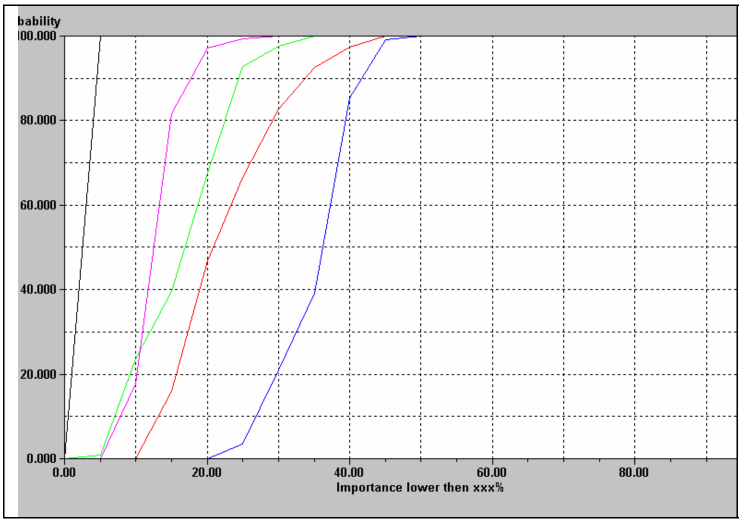


From left to right:
black constant
red lat. acceleration
lime roll velocity
blue jerk
fuchsia; 'N_{VA}

Jerk is the most important parameter followed by lateral acceleration and roll speed.

Figure 12-7 *Importance of each parameter in the regression model.*

12.2.6 Cumulative importance of each parameter



black constant
red Lat. acceleration
lime roll velocity
blue jerk
fuchsia; '*NVA*

Figure 12-8 *Cumulative importance of each parameter of the regressions model.*

12.2.7 Conclusions

1. The correlation of the results is very low.
   Due to the number of observations, this is acceptable, taken into account that a human being has a wide spread in their comfort estimation. This is true both for differences in comfort estimation given by one individual on different occasions, and for differences between different individuals in identical situations.
2. The regressions found are very sensitive to the choice of points taken into regression. This lack on robustness is a negative point for the study.
3. In spite of this difficulty it was possible to propose a regression that has a fair confidence from the associated T parameters.
4. Comparing the quality of the results of local comfort with the quality of the results of average comfort, both are sensibly comparable.
5. The standard deviation of errors in both studies is about 0.7 comfort units.
6. On curvaceous track the main influences are jerk and peak to peak lateral acceleration.

13 Conclusions

13.1 Conditions

13.1.1 Environmental conditions of the tests

The test was executed on a good quality level track and with an excellent quality of the train.

This was also the purpose of the test. (See 7.2 and 7.3). A good spread of input data ensures a good quality of regression analysis. This was true for local comfort because there were different types of curves selected. However, for average comfort the chosen track was too uniform in quality to produce a good spread in the input data.

The resulting evaluation procedure may underestimate the comfort on low quality lines or low quality track.

13.1.2 Extrapolation of results

Because of the budget limitation, it was possible to execute line tests only on one test track, one train and one nationality. This makes the extrapolation of the results to other countries less certain because the track layout and coach construction can differ from one country to another. Moreover different nationalities can have different opinions in comparable situations. The workgroup considers that a second test in a different country would sufficiently improve the range of possibility to extrapolate the results to other situations.

13.1.3 Calculation procedure

It is demonstrated that the averaging/filtering procedure has an important influence on the numeric value of the parameters in the regression. (See appendix two). Other procedures will produce other values of the parameters and consequently other weighting coefficients in the regression which themselves will remain identical in the choice and the participation. The actual proposed evaluation procedures and the associated calculation procedures, explained in appendix one, are strictly connected.

13.2 General impressions on the quality

13.2.1 The comfort evaluation is linear in the conditions covered by the tests

In spite of some visual impressions of the responses of the test subjects, their average ride comfort responses can be considered as linear.

13.2.2 The description of the comfort is sufficiently good to describe the comfort differences due to the seat position

In the raw study of experimental data, it was found that differences did exist between the seating positions. (See Figure 10-5).

These differences become small after applying the proposed evaluation models.

13.3 Conclusions in relationship with the organisation of tests

13.3.1 Choice of the test track

The test track should be chosen in such a way that all relevant situations are present in a sufficient number (See.7.2).

13.3.2 Choice of the test vehicle

It is necessary to be able to control the settings of the tilting control system of the test vehicle in order to obtain a sufficient spread in potential results. (See 8.4.2).

13.3.3 Choice of place in the coach

It is obvious that ideal positions in the coach, having the "optimal compensation" are present in limited number. The number of "optimal" and "non optimal" positions should be optimised to obtain best results. (See 8.4.3).

13.3.4 Synchronisation

It is important to synchronise the questioning of test people as well as possible with the zones to be judged, if possible independently in each vehicle. (See 8.3.3).

13.3.5 Nature of the databases

The working group only had access to a restricted database. This database contained only evaluated values chosen by the working group and allowed by the owners of the test vehicle.

Without any doubt, the possession of a digital time history of relevant data would be a decisive advantage in this kind of investigation, because the possibility to create "on the fly" parameters that seem better adapted to the problem. (See 8.5.2).

13.3.6 Number of events in the experimental database

Due to the natural spread of responses with a human origin (votes), the number of independent data present in the experimental databases should be as large as possible.

The actual average comfort test is based on 153 independent observations, for 4 parameters. 40 observations/parameters is to be considered as an absolute minimum. (See 12.2.7).

13.4 Interpretation of the results

13.4.1 Many parameters are correlated

Many of the parameters initially chosen as possible influences are correlated. The parameters having the lowest mutual correlation factors and giving highest statistical quality are chosen. So it is possible to find other groups of parameters having nearly equal statistical description. (See chapters 11 and 12).

13.4.2 Parameters representing shorter events do give better statistical results

Initially parameters representing the averaged value, calculated on 0.1, 0.4 and 1 second were introduced into regression. Maximum values of 0.1 second averaged values give better statistical results. (See Table 11-5 and Table 11-6).

13.4.3 The spread of the votes is considerable

As could be expected, the spread of the votes in identical situations is important. This is conforms with the spread already observed in the study of equal sensation curves. As a consequence a large number of test persons are needed. Thirty-two test-persons are an absolute minimum to obtain acceptable results. More convincing results will be obtained using 80–100 test persons.

13.4.4 The individual influences are well defined by their associated *t*-parameters

In spite of the spread, the statistical parameters associated with the regressions confirm without hesitation the chosen parameter as "non-zero". (See most of the regression tables).

13.5 Influence of construction details

Construction details of the train as well as the tilt control system do have an influence on the comfort of the people in the train, because it is impossible to balance the lateral acceleration with the same amount of tilt for all position in the vehicle, i.e. the time delay can only be zero for one position in the vehicle. (Time delays of the order of 100 ms or less are probably not noticeable and have no influence on comfort). (See chapter 9).

13.5.1 Influence of the length of the transition

In a transition curve, the tiling angle of the car body is only optimal for one position in the vehicle. The longer the transition curve the smaller is the difference in lateral acceleration felt by a passenger seated in the front of the vehicle in comparison with the lateral acceleration felt by a passenger seated at the end of the same vehicle.

(Short transition curves have other disadvantages such as high levels of roll velocity, roll acceleration and jerk).

13.5.2 Influence of the length of the vehicle

The length of the coach has an influence on the balance of forces, because of the difference between the local radius of the transient curve under the centre of the bogies. (See 9.4.2).

13.5.3 Influence of the control of the tilting system

The synchronisation between the beginning and end of the transition curve and the beginning and end of the tilting motion should be as accurate as possible to avoid the problem with time delay between tilt motion and lateral acceleration at the track level. Time delays provoke both unnecessary levels of lateral accelerations and jerks.

An identical observation can be made, if the train changes speed while driving in curves and/or transitions. Here the time delay between the changing of the speed and the proper changing of the tilt angle should be minimised. (See 9.4.2).

13.5.4 Influence of compensation rate

The higher the compensation level, the higher the influence of non optimal construction and tilt control details. (See Figure 9-7and Figure 9-8).

13.5.5 Influence of train speed

If for some reason the speed is not constant during driving on transitions or circular curves, it is difficult for the tilting system to react properly and the consequences for the comfort are evident.

13.6 Global impressions of the comfort influences

13.6.1 Track and train used in test were of excellent quality

The test has been done on good quality track using a good quality train.

This conforms with the objective of the research, finding a method for the evaluation of comfort using tilting trains travelling at appropriate speeds on curved track.

This means that the evaluation procedure is valid for this type of utilisation, but that for other situations evaluation should be done with care and that maybe (travelling on straight track) the classic evaluation procedure has priority.

13.6.2 Maximum values give best comfort description

The statistical parameters indicate a better description of the phenomena if maximum parameters are used for the description of local comfort in transitions and average comfort. See Table 12-5 and Table 12-6.

13.6.3 Influence of lateral acceleration remains dominant

In this general study, the lateral acceleration in the car body, and jerk remain the main causes of discomfort in transitions.

13.6.4 Influence of rotational acceleration is significant

For the description of local comfort in curves the use of the roll acceleration parameter gives a better description for comfort then the roll speed parameter.

The roll acceleration parameter was not present as a possible choice for the average comfort study. See Figure 11-8 and Figure 12-7.

13.7 Proposed evaluation procedure

All parameters have to be calculated as described in appendix 1.

13.7.1 Evaluation of local comfort on curve transitions

Table 13-1 *Recommended model for estimation of local comfort in transitions curves.*

Object: All transitions				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.651	645.0	3518
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.383	15.8	30%
	$\ddot{y}_{0.1\max}$	0.635	27.2	38%
	$\dddot{y}_{0.1\max}$	0.146	10.5	16%
	$\ddot{\theta}_{0.1\max}$	0.032	9.9	16%

All parameters but N'_{VA} are based on 0.1 second averages; N'_{VA} is a 5 second based average.

13.7.2 Evaluation procedure for local comfort, optimised for track engineers

Table 13-2 *Recommended model for estimation of local comfort using lateral acceleration, jerk and full velocity.*

Object: All transitions with roll velocity – 1.0 second averaging				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.517	428.1	3518
	Probability	< 0.1%	< 0.1%	
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	$\ddot{y}_{1.0\max}$	0.791	18.9	43%
	$\dddot{y}_{1.0\max}$	0.240	3.2	6%
	$\dot{\theta}_{1.0\max}$	0.129	13.3	25%
	intercept	0.479	11.1	26%

13.7.3 Evaluation of local comfort in circular curves

Table 13-3 *Recommended model for estimation of local comfort in circular curves.*

Object: Circular curves and Straight Track (all data)				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.645	266.1	1121
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N'_{VA}	0.490	14.6	43%
	$\ddot{y}_m$	0.780	23.1	38%
	$\ddot{y}_p$	0.661	6.7	19%

$\ddot{y}_m$ and $\ddot{y}_p$ are calculated as described 14.2.3.

13.7.4 Evaluation of average comfort

Table 13-4 *Model for estimation of average comfort on curved lines.*

Object: Average Comfort				
Regression		**Correlation**	***F*-value**	**Observations**
	Value	0.405	25.0	512
Detail	**Parameter**	**Coefficient**	***t*-value**	**Typical Contribution**
	N_{VA}	0.094	1.3	13%
	$\ddot{y}$	0.601	4.5	26%
	$\dot{\theta}$	0.111	3.4	21%
	$\dddot{y}$	0.371	4.5	40%

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1 Preparing the test data from the recorded data for local comfort evaluation

For the local comfort, the data needed for statistical analysis were calculated directly from the recorded database by calculation of the average values on a 0.1 second, 0.4 second and 1 second time base.

For each parameter, the maximum value in the local test zone was used in the statistical analysis. The maximum value was chosen on the basis of previous experiments.

2 Preparing the test data from the recorded data for average comfort evaluation

2.1 Original database

The original databases is the result of sampling at 512 Hz of a continuous time history.

$\Delta t = 1/512\,\text{sec}$ = 0.001953 sec. So each 0.1 second has on average 51.2 values

$\ddot{y}_i, \quad \ddot{y}_i, \quad \dot{\theta}_i$

1 = 0..*N*

2.2 Converted database

From this database we construct a second database representing 0.1-second averages. For doing this we consider two methods:

Method 1: real averaging;

j:=1…*n*

n equals about *N*/51.2

k: = trunc(51.2*j) where “trunc” means the integer part of the real number.

k is the data number which is the nearest to the time *j**0.1 seconds.

Averaging (each $\ddot{y}[j]$ is the average value of 52 consecutive values)

$$\ddot{y}[j] = \frac{1}{52}\sum_{i:=k-51}^{k} \ddot{y}[i]$$

$$with \quad k = trunc(j * 51.2)$$

Method 2:

First apply a low pass filter 2 Hz to the original database giving the same number of data with an identical time interval. $\ddot{y}_{fil\ i}, \quad \ddot{y}_{fil\ i}, \quad \dot{\theta}_{fil\ i}$

Select from this filtred database those values who are nearest to the *k**0.1 second numbers

$$\ddot{y}[j] = \ddot{y}_{fil}[k]$$

$$with \quad k = trunc(j * 51.2)$$

$$\ddot{y}_{fil}\ is\ 2hz\ \ filtered\ value$$

Another way, is two resample the filtered database to a sampling frequency that is a multiple of 10 Hz. Then it is easy to average a whole number of samples.

Now we have a basic “converted” database with values in 0.1 seconds distance (with a very acceptable approximation).

The working group favoured the second method

2.3 Create extended converted database with additional data y"$_p$ and y"$_m$

$\ddot{y}_j, \quad \dddot{y}_j, \quad \dot{\theta}_j$

For each "j", create a group with the 20 next data (= 2 seconds)
' j represents a data of the 0.1sec group
Sort this group
Calculate

$\vee\ 0 <= j <= n-19\ do$

$sort\,(\ \ddot{y}[j]..\ddot{y}[j+19]) \quad ascending$

$\ddot{y}_p[j] := \ddot{y}[j+19] - \ddot{y}[j]$

$$\ddot{y}_m[j] := \frac{\ddot{y}[j+9] + \ddot{y}[j+10]}{2}$$

We now have:

$\ddot{y}[j], \quad \dddot{y}[j], \quad \dot{\theta}[j], \quad \ddot{y}_m[j], \quad \ddot{y}_p[j]$ for each 0.1 second

2.4 Create a condensed database

From this basic converted database we construct a 5sec condensed database in the following manner.

5 seconds means 50 values.

p is the number of 5 second blocks from "0" to "m"

$\ddot{y}[p] = \max(\ddot{y}[p*50 \cdots \ddot{y}[p*50+49])$

$\dddot{y}[p] = \max(\dddot{y}[p*50 \cdots \dddot{y}[p*50+49])$

$\dot{\theta}[p] = \max(\dot{\theta}[p*50 \cdots \dot{\theta}[p*50+49])$

$\ddot{y}_m[p] = \max(\ddot{y}_m[p*50 \cdots \ddot{y}_m[p*50+49])$

$\ddot{y}_p[p] = \max(\ddot{y}_p[p*50 \cdots \ddot{y}_p[p*50+49])$

2.5 Publish result

Now for each 60 blocks denominated by "*q*" of 5 seconds we construct the following procedure:

$$sort\ (\ddot{y}[q]\cdots\ddot{y}[q+59])\quad ascending$$
$$sort\ (\ddot{y}[q]\cdots\ddot{y}[q+59])\quad ascending$$
$$sort\ (\dot{\theta}[q]\cdots\dot{\theta}[q+59])\quad ascending$$
$$sort\ (\ddot{y}_m[q]\cdots\ddot{y}_m[q+59])\quad ascending$$
$$sort\ (\ddot{y}_p[q]\cdots\ddot{y}_p[q+59])\quad ascending$$

Then publish maximum values

MAX	95 % values	Mean values
$\ddot{y}[q+59]$	$\ddot{y}[q+56]$	$(\ddot{y}[q+29]+\ddot{y}[q+30])/2$
$\ddot{y}[q+59]$	$\ddot{y}[q+56]$	$(\ddot{y}[q+29]+\ddot{y}[q+30])/2$
$\dot{\theta}[q+59]$	$\dot{\theta}[q+56]$	$(\dot{\theta}[q+29]+\dot{\theta}[q+30])/2$
$\ddot{y}_m[q+59]$	$\ddot{y}_m[q+56]$	$(\ddot{y}_m[q+29]+\ddot{y}_m[q+30])/2$
$\ddot{y}_p[q+59]$	$\ddot{y}_p[q+56]$	$(\ddot{y}_p[q+29]+\ddot{y}_p[q+30])/2$

1 Preparing data evaluation, precautions and choices

1.1 Introduction

The data used in comfort evaluation are of the type “acceleration” or “speed” and some of their derivatives.

Translation, acceleration and rotational speed are the measured signals in this study.

Jerk and roll acceleration are calculated from the measured signals.

The output signal of the measuring apparatus is sampled at a given rate and then stored digitally.

That output signal not only contains the useful and wanted signal but also a distortion of that signal commonly called noise.

Moreover the recorded signal contains unwanted information not needed for the comfort evaluation.

The separation of the useful signal from the other components can be achieved either by “ averaging” or by “frequency filtering”. In the frequency filters we normally distinguish band-pass filters and weighting filters. Normally averaging and band filtering are used to separate the wanted signal from the noise, while weighting is normally used to optimise the information for evaluation of the criteria.

After averaging and band filtering (before eventually weighting) the signal can be differentiated to obtain jerk and roll acceleration.

Considered in the frequency domain, not all frequencies are equally important for evaluation of comfort. Previous studies have demonstrated that for the evaluation of comfort on straight track, it is sufficient to investigate comfort in the frequency domain starting at 0.5 Hz. Up to 100 Hz Weighting functions are established for vertical and lateral accelerations.

Because of the local character of the phenomena on curvaceous track, study in the frequency domain is less appropriate. Experimental weighting functions don’t exist for roll velocity nor for jerk.

Here the presence of higher frequencies could suggest the occurrence of noise, which can be removed by adequate filtering.

It is clear that the methods used for averaging and band filtering do influence the result, and even more the derived information as jerk and roll acceleration. To optimise these techniques and to evaluate the possible influence of the methods used, we demonstrate their influence on the simulated behaviour of a tilting coach with some roughly estimated characteristics travelling on a part of the real test route.

1.2 Basic conditions of simulation

The data in the real tests are sampled with 512 Hz meaning a Δt=0.004 sec.

In this study; a time window of 200 seconds is used giving a Δf=0.005 Hz.

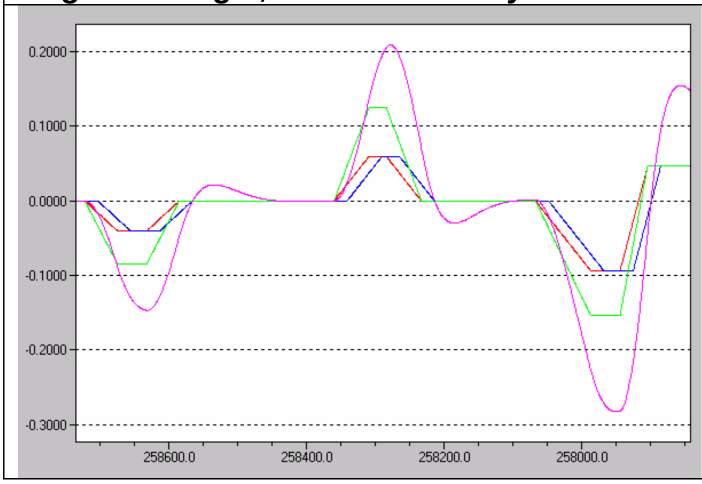
There are 16384 data points per sample so Δt = 0.012207 sec

Basic curves are a rough estimation of vehicle behaviour in curves and curve transitions, taking into account a programmed remaining lateral acceleration of 0.5 m/s^2.

For this program then the angle of the coach is given by the track position and the tilting mechanism. The latter is so programmed that *RLA* in curve is equal to $0.5 m/s^2$.

The lower part of the frequency spectrum, especially for roll acceleration, is strongly influenced by the first resonant frequency of the tilting body in the sway mode. So the images below have to be considered as a first impression. This first impression is sufficient for the considerations developed in this chapter.

The basis of the program is the calculation of the absolute coach angle from the position of both bogies and the action of the tilting system as an input to a vibration system with one degree of freedom with a given damping and give resonant frequency, as illustrated below.

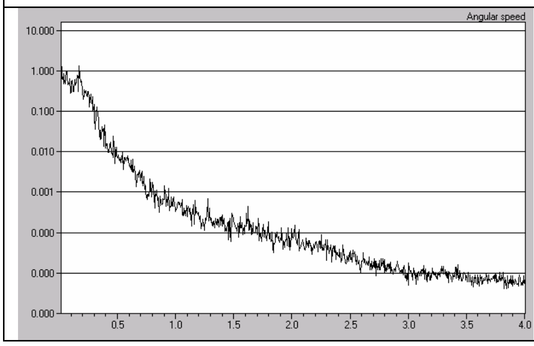
Angles of bogie, tilt and car body	
	Red line: angle position first bogie Blue line: angle position second bogie Green line: tilting mechanism Fuchsia line: dynamic reaction of the coach.

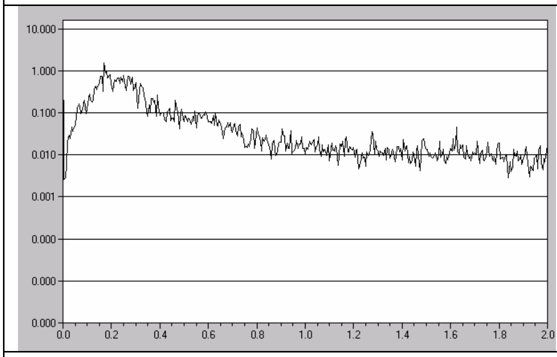
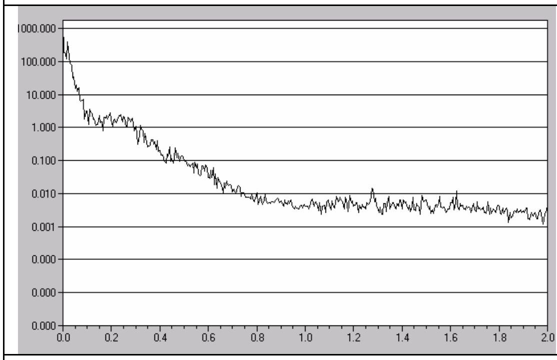
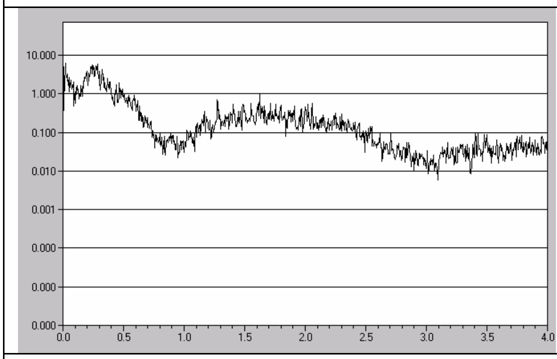
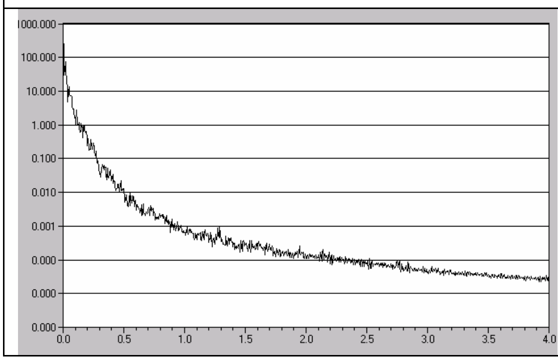
1.3 Influence of low pass filters on amplitudes of the signal

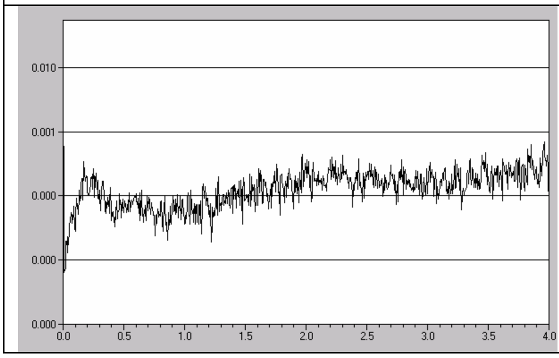
1.3.1 Study in the frequency domain

As most comfort evaluation procedures use weighting functions, it advisable to know the theoretical frequency input of the tilting coach.

The figures below give the estimated energy density for a part of the test track.

Spectrum of roll velocity	Energy between spectrum lines
	<= 0.2 HZ 0.04 rad/s > 0.2 Hz 0 rad/s

Roll acceleration	Energy between spectrum lines
	<= 0.2 HZ 0.05 rad/s^2 > 0.2 Hz 0.01 rad/s^2
Lateral acceleration (middle position)	Energy between spectrum lines
	<= 0.2 HZ 0.30 m/s^2 > 0.2 Hz 0.01 m/s^2
Jerk	Energy between spectrum lines
	<= 0.2 HZ 0.13 m/s^3 > 0.2 Hz 0.06 m/s^3
Vertical acceleration	Energy between spectrum lines
	<= 0.2 HZ 0.15 m/s^2 > 0.2 Hz 0.01 m/s^2

<table>
<tr><td>Vertical acceleration (Elevation)
Estimation of vertical displacement due to track cant and tilt.</td><td>Energy between spectrum lines</td></tr>
<tr><td>
</td><td><= 0.2 HZ 0. m/s^2
> 0.2 Hz 0.03 m/s^2</td></tr>
</table>

Conclusion

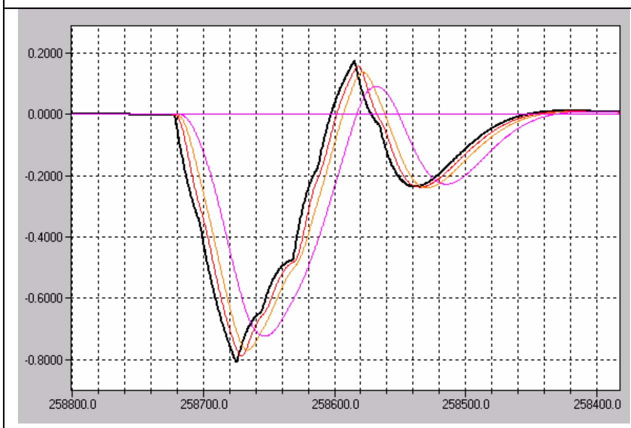
As a conclusion, globally energy above 2 Hz is nearly absent in the frequency domain description for the theoretical dynamic behaviour of coaches on curvaceous track

It can't been excluded that the classic low pass cut-off frequency [2 Hz] has an important influence on the filtered result and so on the maximum values. This conclusion can alter if the filter is used to eliminate noise from the recorded signal and therefore the cut-off frequency is lowered.

However, the very low frequency part is abundant, so the cut-off frequency and the high pass characteristic of the band filters are important.

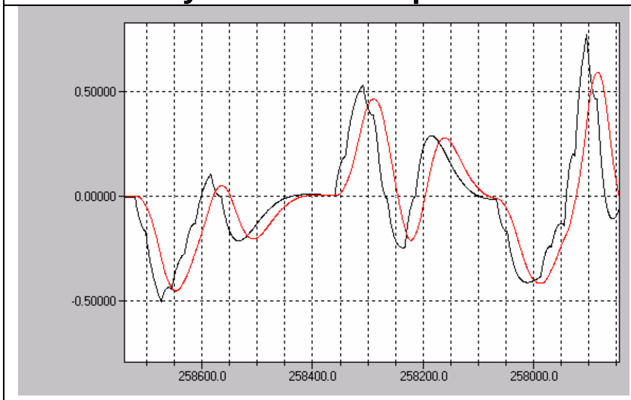
It is also uncertain how the Jerk calculation is influenced by previous filtering and/or averaging.

1.3.2 Influence of low pass filters on maximum values - study in time domain

<table>
<tr><td>Influence of the low pass filter on maximum values of lateral acceleration</td><td></td></tr>
<tr><td>
</td><td>In this figure, representing lateral acceleration, three low pass filters are applied: 2, 1 and 0.5 Hz.

The influence on the maximum value is a slight decrease and lower peaks

The influence becomes noticeable for 1 Hz and lower.</td></tr>
</table>

Detail study of 0.5 Hz low pass filter	
	Filter 0.5 Hz The influence on amplitudes is small but noticeable.

Conclusion

The influence of filtering below 1 Hz becomes significant for the magnitude of maximum lateral acceleration values, as could be expected from previous paragraph.

1.3.3 Influence on jerk

How to calculate derivatives

Jerk can be calculated with different formulae, different averaging and different low pass filtering.

First order formula

$$f'(x) = \frac{f(x+h) - f(x-h)}{2h} \quad (1)$$

(1) This formula is symmetrical relative to *x* like the second order method

Second order formula

$$f'(x) = \frac{8f(x+h) - f(x+2h) + f(x-2h) - 8f(x-h)}{12h} \quad (2)$$

Differences between (1) and (2) do exist but are very small and without noticeable influence.

PCT formula

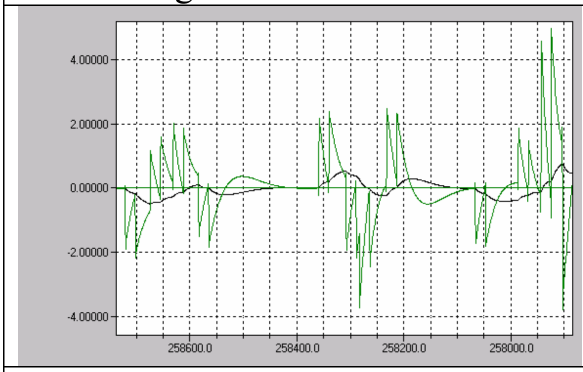
$$f'(x) = \frac{f(x+xh) - f(x)}{xh}$$
$$x \times h = 1\,\text{sec} \quad (3)$$

Differences between (2) and (3) are discussed further in this text.

Influence of low pass filter on jerk

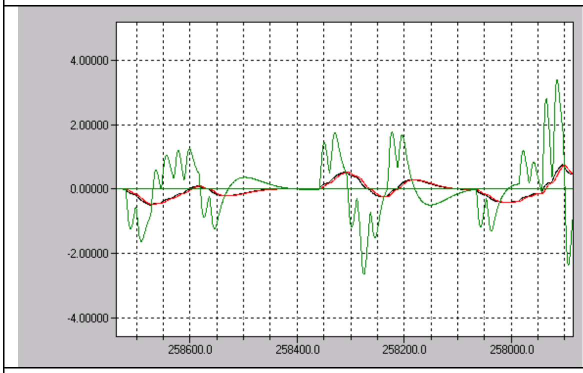
The filtered lateral acceleration is used as input for the calculation of the derivative. Formula 2 is used for the calculation of the derivative.

No filtering



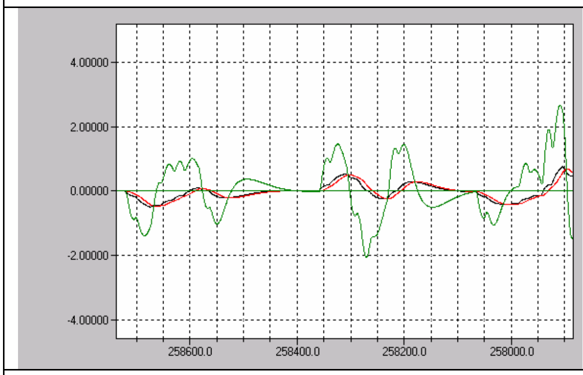
Peak at 258231 m
height 2.48 m/s^3

Filter 2 Hz



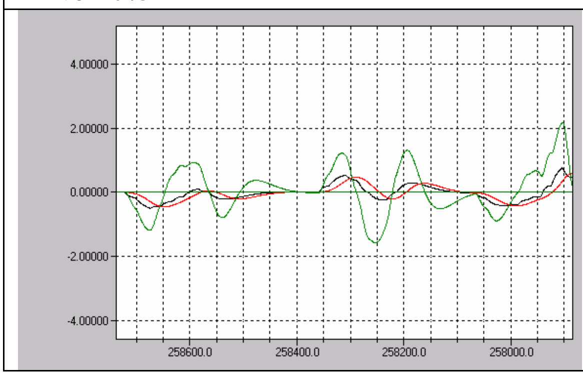
Peak at 258224 m
height 1.78 m/s^3

Filter 1 Hz



Peak at 258217 m
Height 1.34 m/sec^3

Filter 0.5 Hz



Peak at 258194 m
height 1.31 m/sec^3
(two peaks now merged to one)

1.3.3.3 Conclusion

All filters do have an important consequence on the result

A 0.5 Hz low-pass filter does give unacceptable results?

The filter used must be included in the standard rules in order to obtain comparable results.

1.4 Influence of averaging on amplitudes

1.4.1 Discussion on taking averages

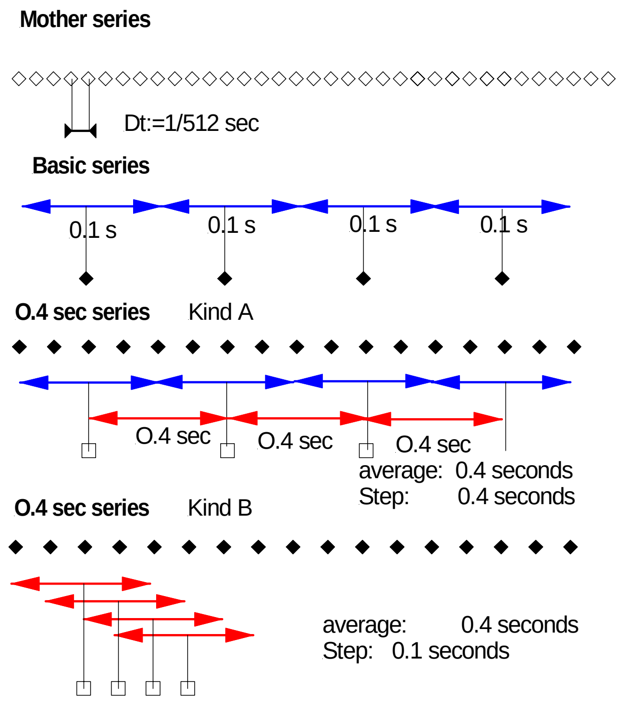


Figure 14 *Model for reducing and average a time histories.*

This mother series contains much more data detail than is needed.

For comfort estimation, all except vertical vibrations are only of interest in the small frequency zone 0.5 to 2 Hz.

Whether this is also the case for the parameters describing the influence of transition curves and curves, strictly speaking, is uncertain but likely taking into account previous analysis.

We can reduce the information quantity in the time series by two ways

1. averaging the data series
2. applying a low-pass filter.

In this chapter, the first method is discussed.

From the mother series we construct a basic series with different time basis.

Average for 0.1 second , 0.4 second and 1 second.

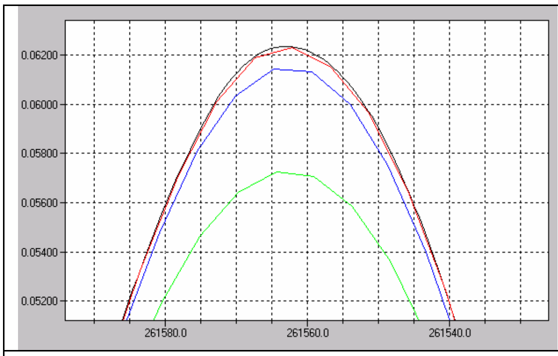
This can be done in two different ways (kind A and kind B).

It can be demonstrated that a step = 0.1 second is the only feasible method.

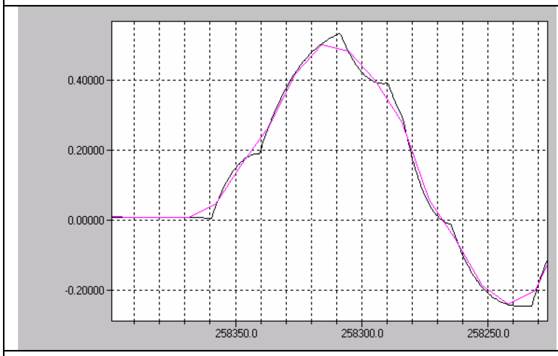
All other steps give non useful results (this is in agreement with the P_{CT} rules).

1.4.2 Influence of averaging on lateral acceleration

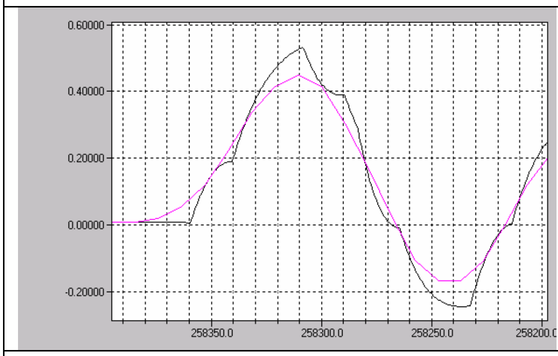
Application of averaging in some examples



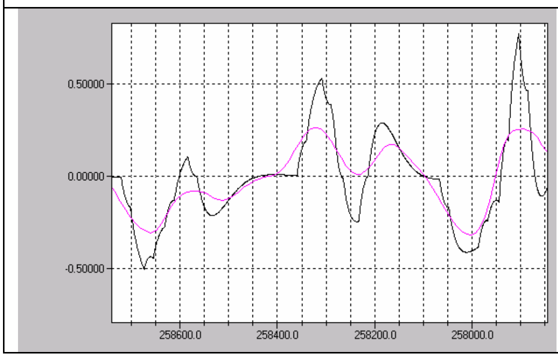
Red line : 0.1 second average, step 0.1 second
Blue line: 0.4 second average, step 0.1 second
Green line: 1 second average, step 0.1 second



0.1 second average
0.1 second step



0.4 second average
0.1 second step



1 second average
0.1 second step

Conclusion

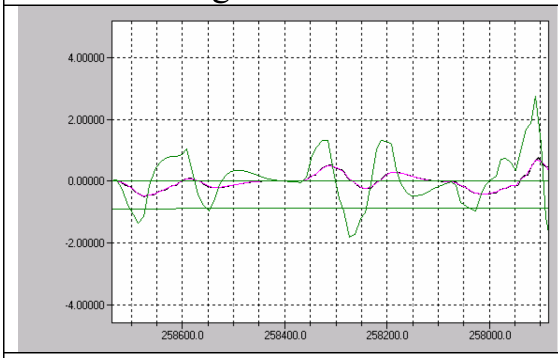
0.1 second and 0.4 second averaging seem harmless, but 1 second averaging seriously changes aspects of RLA.

Note it is shown in this report that 0.1-second averages do give the best results.

1.5.1 Influences of averaging on jerk

Influences of averages on calculation of derivative

0.1 sec average

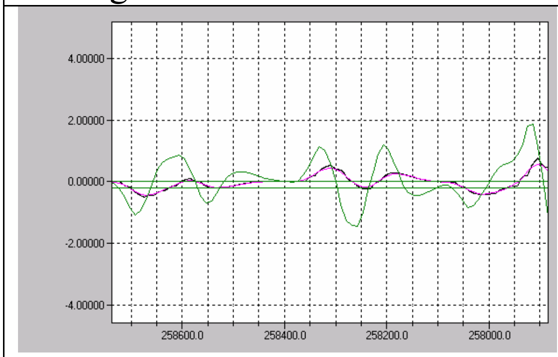


0.1 second step

peak at	2.58211 m
height	1.31 m/s^3

Seems comparable with 0.5 Hz filtering.

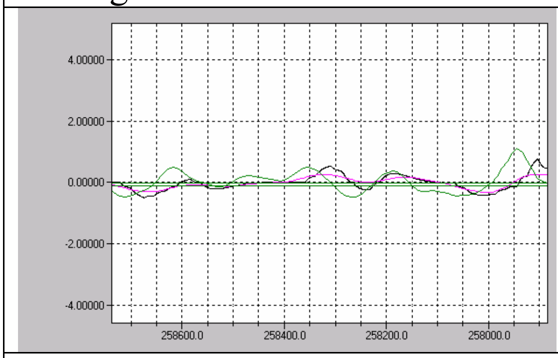
Average 0.4 sec



0.1 second step

peak at	2.58207 m
height	1.20 m/s^3

Average 1 sec



0.1 second step

Peak at	2.58188 m
Height	0.38 m/s^3

Zoom of previous image

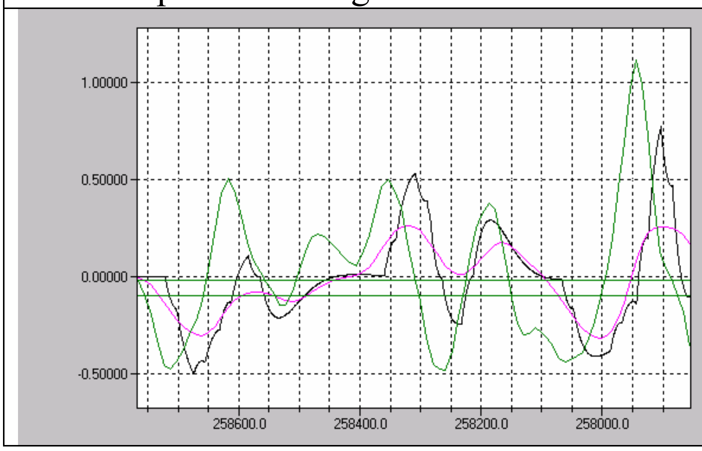
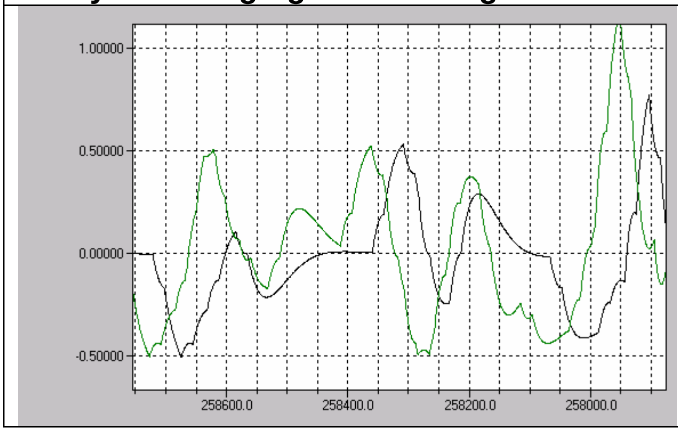


Figure 22
Black line: Original signal
Red line : Averaged signal
Green line: Derivative.

Study of averaging and filtering



Filter 0.5 Hz

Same zone as before

P_{CT} method for calculating jerk

Straight method

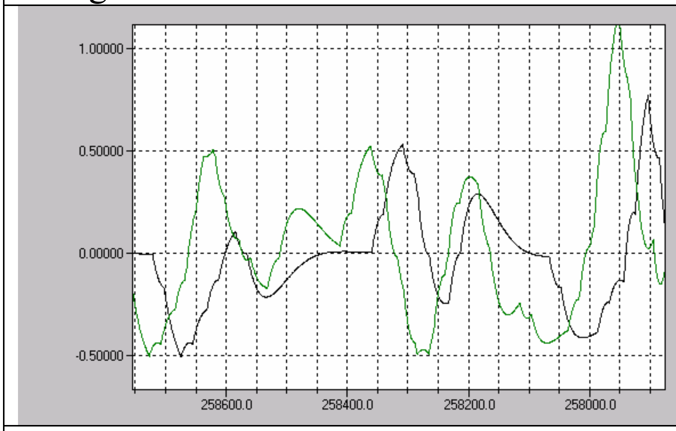


Figure 24
no averaging

Peak at	258198 m
Height	0.38 m/s^3

Average 0.1 second

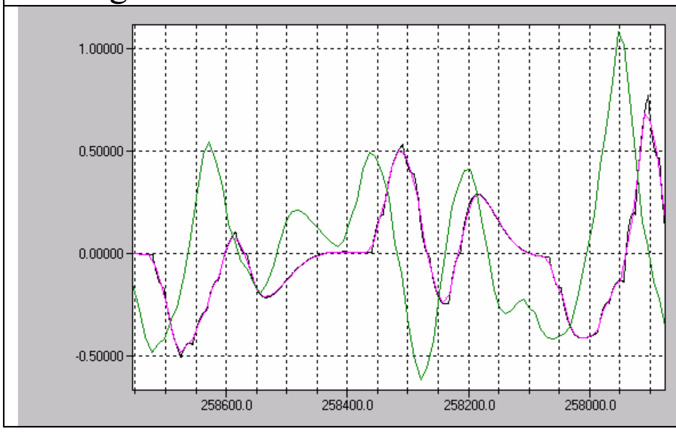


Figure 25
0.1 second step

Peak at	2.58197 m
Height	0.41 m/s^3

Conclusion

The 0.1 sec average is very comparable with the non averaged signal.

The P_{CT} method is very comparable with the 1 second averaging method. This means that significant information can been lost from the data. However it is not known if this leaked information is important for comfort determination.

1 International and European ride comfort standards

There exist a number of standards concerning guidelines for evaluation comfort and health. The most used one is ISO 2631-1 (1997) *Mechanical vibration and shock – Evaluation of human exposure to whole body vibrations – Part 1: General requirements.* This standard has evolved from guidelines on fatigue and comfort degeneration of a number of hours exposure to a straight forward root-mean-square (r.m.s.) calculation of a frequency weighted or filtered acceleration signal.

ISO-comfort note = $[1/T \int a_w^2(t)\,\mathrm{d}t\,]^{0.5}$

where a_w is a filtered signal according to different weighting filters, w_d for lateral accelerations and w_k for vertical accelerations, see chapter of weighting curves for filtering below. For railway purposes the weighting filter w_b is allowed for vertical accelerations.

Guidance according to ISO 2631-1		CEN (ENV 12299)	
Less than 0.0315 m/s^2	not uncomfortable	Less than 0,17 m/s^2	Very comfortable
0.0315 to 0.63 m/s^2	a little uncomfortable	0.17 to 0,33 m/s^2	Comfortable
0.5 to 1 m/s^2	fairly uncomfortable	0.33 to 0,50 m/s^2	Medium
0.8 to 1.6 m/s^2	uncomfortable	0.5 to 0,67 m/s^2	Uncomfortable
1.25 to 2.5 m/s^2	very uncomfortable	0.67 to 0,83 m/s^2	Very uncomfortable
Greater than 2 m/s^2	extremely uncomfortable		

Note: To have a good understanding of this table: the mentioned acceleration is the square root of quadratic sum of all accelerations present in the evaluation formula. (For CEN the simplified formula is chosen as estimator for the "total acceleration").

ISO 2631-1 is good for evaluation of motion environments with small variations in levels. However characteristics of a train ride is there are large variations (fluctuations) in both acceleration levels and frequency and also there exist sudden impulses, jolts and changes of quasi-stationary levels.

The work in ORE and ERRI during Questions B 153 and B207 was to address these fluctuations with statistical methods. Together with the work at former British Rail Research in Derby on comfort in transition curves and circular curves, these two works formed the basis for the European standard CEN ENV 12299 (1997, 1999) *Railway applications – Ride comfort for passengers – Measurements and evaluation.*

The statistical methods were also incorporated in an ISO standard, ISO 10056 (1996) *Mechanical vibration - Measurement and analysis of vibration to which passengers and crew are exposed in railway vehicles* and in the UIC rules, UIC Leaflet 513 R. *Guidelines for evaluating passenger comfort in relation to vibration in railway vehicles.*

Later it seemed appropriate to update ISO 2631 with a new part concerning railway applications, ISO 2631-4 (1999) *Mechanical vibration and shock –*

Evaluation of human exposure to whole-body vibration – Part 4: Guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed guideway transport systems. This standard allows the statistical method as a way to analysis vibrations.

All these standards give guidelines for the evaluation of average comfort on mostly straight lines and not lines with many curves.

Comfort on curvaceous lines has not been incorporated in any international standard.

2 Weighting curves

Weighting curves are defined according to ISO 2631-1 and BS 6841, see Figure 1.

w_b Weighting curve for vertical accelerations for comfort and health according to BS 6841:1987 (BSI 1987). w_b is used for comfort evaluation according to the CEN standard (CEN 1996b). w_b is not the primary weighting curve for vertical acceleration according to ISO 2631-1 but is acceptable for railway applications (ISO 1997).

w_d Weighting curve for lateral and longitudinal accelerations for comfort and health according to ISO 2631-1 (ISO 1997).

w_k Weighting curve for vertical accelerations for comfort and health according to ISO 2631-1 (ISO 1997).

w_f Weighting curve for vertical accelerations for evaluation of motion sickness according to ISO 2631-1 (ISO 1997).

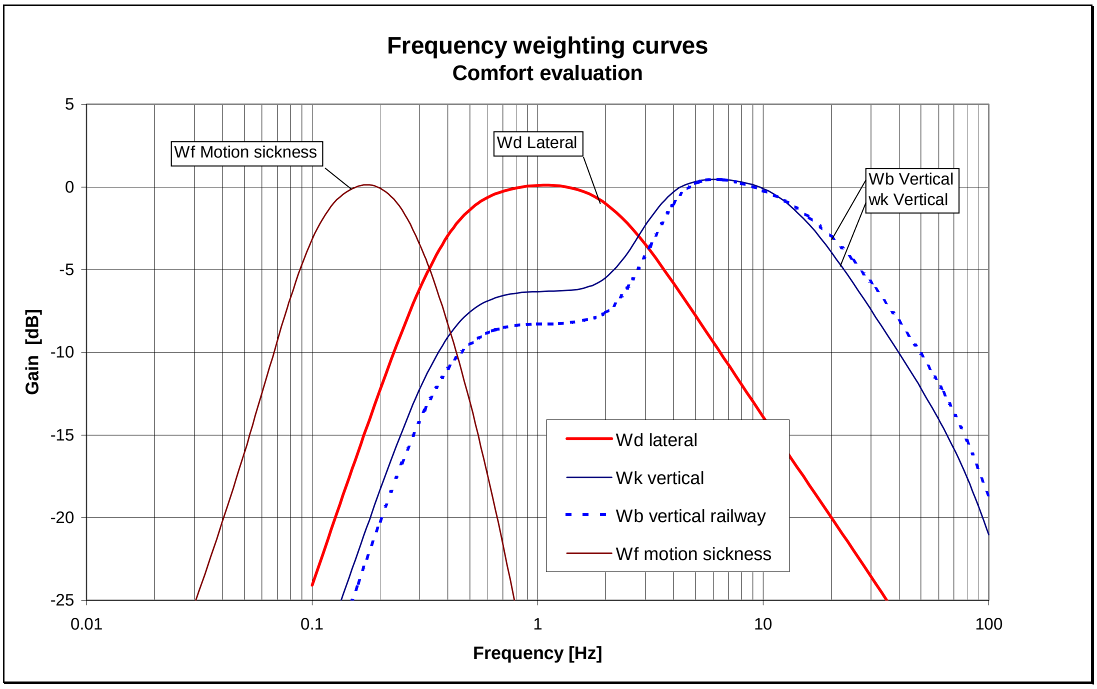


Figure 1 *Weighting curves w_k, w_d, w_f (ISO 2631-,1 1997) and w_b (BS 6841:1987, 1987).*