FINAL TECHNICAL REPORT

CONTRACT N°: 1999-RD.10442

PROJECT N°: B99/99/S12.107978-B66131122

ACRONYM: STAIRRS

TITLE: Strategies and Tools to Assess and Implement Noise Reducing Measures for Railway Systems

PROJECT CO-ORDINATOR: European Rail Research Institute

PARTNERS :	**ERRI**	**TNO**
	SBB	**Poli**
	SNCF	**ETHZ**
	AEAT BV	**ULB**
	DBAG	**ISVR**
	PsiA	

REPORTING PERIOD : FROM 1 January 2000 TO 31 December 2002

PROJECT START DATE: 1 January 2000 DURATION :3 years

Date of issue of this report: 18 December 2003

Document Reference: STR40TR181203ERRI

Project funded by the European Community under the 'Competitive and Sustainable Growth' Programme (1998-2002)

Amendments

Version number	Amendment details	Date (dd.mm.yy)
6	Draft	23.10.03
9	Comments from Consortium	20.11.03
10	Final Review by Project Management Group	18.12.03

Approval by Project Management Team

Prepared by	Reviewed by	Approved by
Brian Hemsworth	Consortium	Project Management Group

Distribution List (final version only)

Organisation	Number of copies
EU DG TREN	1 electronic version + 3 paper copies
SBB	1 electronic version
SNCF	2 electronic versions
DB AG	1 electronic version
AEAT	1 electronic version
Psi-A	1 electronic version
TNO	1 electronic version
POLI	1 electronic version
ULB	1 electronic version
ETHZ	1 electronic version
ISVR	1 electronic version
UIC	1 paper copy

Table of Contents

Table of Contents

Executive Summary ***1***

1 Objectives of the Project ***3***

1.1 WP 1: Railway Noise Strategy Support System 3
1.2 WP 2: Characterisation & Classification Methodologies 4
1.3 WP 3: Consensus Building Workshops 5

2 Scientific and technical description of the results ***5***

2.1 Work Package 1 5
2.1.1 Summary 5
2.1.2 Noise Calculation 6
2.1.3 Noise Mitigation Scenarios 11
2.1.4 Cost Effectiveness Functions 15
2.1.5 Extrapolation 23
2.1.6 Optimisation 28
2.1.7 Cost Effectiveness Analysis 31
2.1.8 Suggestions for further study 33
2.2 Work Package 2 35
2.2.1 Separation Techniques 35
2.2.2 Combining Separately Measured Vehicle and Track Components of Noise... 52
2.2.3 Measurement Procedure for Separation Techniques 54
2.2.4 Measurement Campaign and Data base 64
2.2.5 Improvements to procedure for rail roughness measurements 66
2.2.6 Classification 77
2.3 Work Package 3 Consensus Building Workshops 83
2.3.1 Introduction 83
2.3.2 1st Workshop, Brussels, 23 March 2000 83
2.3.3 2nd Workshop, Paris, 6 & 7 March 2001 83
2.3.4 3rd Workshop, Paris, 5 & 6 March 2002 84
2.3.5 4th Workshop, 26 November 2002 85

3 Deliverables/Milestones/Progress reports ***85***

3.1 Deliverable D1 85
3.2 Deliverable D2 85
3.3 Deliverable D3 85
3.4 Deliverable D4 86

3.5 Deliverable D5 ... 86
Deliverable D5a ... 86
Deliverable D5b ... 86
1.7 Deliverable D6, ... 86
Deliverable D6, Overview report ... 86
Deliverable D6, Part 1 ... 87
Deliverable D6, Part 2 ... 87
Deliverable D6, Part 3 ... 87
3.6 Deliverable D7 ... 87
3.7 Deliverable D8 ... 87
3.8 Deliverable D9 ... 88
3.9 Deliverable D10 ... 88
Annex 1 ... 88
Annex 2 ... 88
Annex 3 ... 88
Annex 4 ... 88
3.10 Deliverable D11 ... 89
Part 1 ... 89
Part 2 ... 89
Part 3 ... 89
Part 4 ... 89
Part 5 ... 89
Part 6 ... 90
Part 7 ... 90
3.11 Milestone 1 ... 90
3.12 Milestone 2 ... 90
3.13 Milestone 3 ... 90
3.14 Milestone 4 ... 90
3.15 Milestone 5 ... 90
3.16 12 month Progress Report ... 91
3.17 Mid Term Report ... 91
3.18 24 Month Progress Report ... 91
3.19 36 Month Progress Report ... 91
3.20 Final Technical Report (Milestone 6) ... 91
3.21 Technological Implementation Plan ... 91
4 Comparison with planned activities ***92***

4.1 Work package 1 ... 92
4.2 Work Package 2 ... 92
4.3 Work Package 3 ... 93
5 Management and Coordination aspects ***94***
5.1 Consortium Contacts ... 94
6 Conclusions ***98***
6.1 Work Package 1 ... 98
6.2 Work Package 2 ... 99
6.3 Work Package 3 ... 100
7 Bibliography ***101***
8 Conference Papers ***106***

Executive Summary

The STAIRRS proposal was submitted in response to the EU's 5th Framework Programme "Sustainable Mobility and Intermodality: Competitive and Sustainable Growth" where the need was identified for a study to assess the relative effectiveness, benefits, and costs of a number of railway noise mitigation options applied to vehicles or track.

The approved project consisted of three technical Work Packages

Work Package 1 would provide a cost benefit software tool to assess various noise mitigation strategies. It was intended that the tool would use existing traffic and noise databases and would be extended to cover those areas not currently served with databases. Capabilities would be provided to derive data at either national or European level. Additionally an optimisation procedure would be developed to determine the optimum mix of noise reduction strategies that could be applied to individual lines.

Work Package 2 would provide measurement methodologies to enable characterisation of railway vehicles and railway track separately. By these means it would be possible to attribute separate responsibilities between infrastructure authorities and train operators in the operation of railways, provide assistance to designers of rolling stock and infrastructure and identify, for specific situations, where noise mitigation could most effectively be applied. A final objective of this work package was to propose a classification methodology for vehicles and tracks based on their noise characteristics.

A series of Workshops were to be organised within Work Package 3 to develop a consensus between legislators, railway operators, railway infrastructure managers and the railway supply industry on the means of balancing the environmental needs of the Community with the noise mitigation options available and the costs of their implementation.

Eleven deliverables and six milestones were planned and these have been completed.

WP1 delivered a cost effectiveness software tool which compares costs (in monetary units) with benefits in (acoustic units). It contains, again as planned, extrapolation modules and optimisation modules. During its development calculations were carried out for a number of countries as part of the validation process. This allowed certain conclusions to be drawn regarding the extent of the railway noise problem in Europe, the costs of alleviating the noise and a priority for options which should be taken. Because of the approximations used in the analysis estimates of costs and number of people above certain noise levels should be viewed with caution. The relative efficiency of the different measures investigated is however valid. These indicate that as a first step ensuring that freight trains have smooth wheels is the most efficient noise mitigation step to take. By itself however it does not achieve sufficient noise reduction to achieve targets being placed on the railways and must be supplemented by further measures taken on wheels and tracks.

The analysis also showed that a combination of smooth wheels, rail absorbers and optimised wheels was more effective than the use of noise barriers, even when 4 m high, at a lower cost.

A number of techniques were developed within WP2 to separate the contribution of wheel and track to total noise. In addition to separating wheel and rail roughness the methodologies determined the roughness to noise transfer function for wheels and tracks thus providing tools that could be used to assess whether particular designs could be designated "low noise".

In order to do this a measurement procedure was developed and validated with a measurement campaign. Results from this measurement campaign may be considered a first step to a European data base on separated train noise levels.

A Series of workshops were held as Milestones in the project and a degree of consensus was reached by delegates representing all elements of the railway industry. When asked *"What has to be done to generate quiet railways?"* at the second workshop it was concluded that pressure from the implementation of noise creation legislation for railways was an essential step for reducing noise levels. It was recognised, however, that some change to the EU funding policies would be needed so that where it was shown to be cost effective, financial support should be given to noise mitigation at source instead of it being used to construct of lineside noise barriers.

At the third workshop a management game was introduced to the participants who used it to attempt to solve a hypothetical railway noise problem by assessing the costs and effectiveness of different noise mitigation options. Through this process it was generally agreed by the delegates that application of operational constraints, even locally, in order to reduce noise was not consistent with the commercial requirements of railway operation particularly whilst attempting to fulfil the objective of transferring traffic from road to rail and needing to maintain competitive with respect to road transport.

The results of the project were presented at the final Workshop.

As part of the communication element of WP3 the STAIRRS website www.stairrs.org became operational during 2000.

At the Mid Term Review (Milestone 3) it was concluded that the project was being performed to schedule, within the allocated costs and that no revision of the work programme for the second half of the project was required. The project therefore continued in its final phases as originally planned.

1 Objectives of the Project

1.1 WP 1: Railway Noise Strategy Support System

Railway organisations in Europe have been involved in National and International research focused on reducing railway noise since the early 1970's. This research has led to a quantitative understanding of the main source of railway noise (rolling noise) and to concepts for reducing it.

This background knowledge has been used in the development of prototype solutions to reduce railway rolling noise through the EU sponsored FP4 projects SILENT FREIGHT, SILENT TRACK and EUROSABOT which focused on freight traffic.

From these projects, indications are that a noise reduction in excess of 10 dB(A) can be achieved using low noise components such as wheels and rails with optimised cross sectional shape, added damping to wheels and rails, shrouded bogies and low trackside barriers.

EUROSABOT focussed on the need for smooth wheel surfaces to minimise noise. This is not possible when using traditional cast iron tread brakes. The objective was to provide a design process that could be used in the development of low wheel roughness, tread brake blocks. In addition, a current initiative is being undertaken by European railways to replace cast iron tread brake blocks by composite brake blocks. This is expected to lead to a noise reduction of between 8 and 10 dB(A)

These mitigation options need to be assessed against the performance of conventional lineside barriers, where a noise reduction in excess of 15 dB(A) is achievable using high barriers (>3m high) with absorbent material on the side facing the railway. Noise reduction of about 20 dB(A) represents the upper limit for the effectiveness of noise barriers.

Thus it can be seen that a number of alternative noise mitigation options are becoming available that are likely to give significant noise reductions. An appropriate mix of options applied to vehicle and/or track can achieve a variety of intermediate noise reduction targets. Environmental noise levels are also affected by operating conditions such as speed, choice of route and time of operation. This latter effect is important when night operations and night time noise legislation are considered.

The noise benefit represents only one side of the equation and where a particular noise reduction can be achieved by different mixes of options, cost and other factors will need to be taken into account to determine the most effective course of action. To date such studies have only been carried out on a national scale, for example in Switzerland and for a few freight routes in Europe for UIC. These studies indicated the benefit in both cost and effectiveness of noise reduction at source on vehicles and tracks as an alternative to the use of noise barriers. These studies need further extension to the European scale to assess where most effort is needed for low noise designs and the acceptable cost of their introduction. The present study will use experience gained from those projects.

Currently none of the tools available are capable of optimising, from a cost and benefit point of view, noise reduction strategies at either local, national or international level.

The objective of WP 1 of STAIRRS is to provide a Europe wide software tool to determine the large scale environmental impact of railway noise. It is intended that the tool will use existing traffic and noise databases to the greatest extent possible. The software must be able to handle large amounts of data in a short amount of time and must be user friendly. The end user of the software will be decision makers at European and national levels as well as members of the consortium.

The software tool can provide the basis for answering the following questions:

- Reduction of Annoyance for different noise policies (benefit).
- The economic effects of policy options (cost).
- Comparison of country specific solutions.
- The consequences of noise measures on the viability of rail transport.

The output of this WP will be a software tool capable of carrying out the assessments identified above, supported by a database of European rail traffic and their noise characteristics, topographical maps and comprehensive cost data for the different noise mitigation options.

1.2 WP 2: Characterisation & Classification Methodologies

Currently specified methods for measuring the noise from individual trains or vehicles in trains are limited in their ability to produce repeatable and reproducible data that can be reliable for the Cost Benefit Analysis of WP1, legislative guidelines or for checking compliance. It is possible that in the future, financial bonus/penalty systems will be introduced for the use of quiet/noisy rolling stock and track types, thus vehicle types and track superstructure types will need to be classified. To implement such a system requires a reliable method for measuring the noise creation of train/track combinations.

Investigation of this topic has been carried out in the FP4 project METARAIL which focused on measurement methods for the assessment of railway noise creation. In that project, which started in 1996, existing methods were tested and further developed and compared to new and innovative methods.

It was demonstrated that:

- ♦ It is feasible to improve the repeatability and particularly the reproducibility of railway pass-by noise measurements significantly by control of track roughness, train speed and site conditions concerning sound propagation.
- ♦ Methods could be developed and optimised through which it is feasible to separate the track and vehicle contribution to the overall noise level. However, these methods need further development and validation before they can be applied and accepted as industrial practice.

Remaining differences between measurement results of the same vehicle on different sites are estimated to be due to differences in:

- ♦ site propagation conditions,
- ♦ track dynamic behaviour,
- ♦ track roughness.

For more repeatable results the values of these parameters need to be accurately identified so that suitable corrections can be applied as necessary.

WP 2 was intended to extend that work with the following objectives:

- ♦ To provide methodologies to enable characterisation of railway vehicles and railway track separately. By these means it will be possible to:
  - ♦ apportion responsibilities between infrastructure authorities and train operators
  - ♦ relate the effects of noise reduction measures on vehicle or track to different situations required for the Cost Benefit Analyses

        - enable data to be transferred from one situation to another e.g. between tracks types, characteristic of different countries, to provide assistance in improving interoperability.
- propose a classification method
- To develop and validate the measurement and associated calculation tools needed to fulfil the methodologies mentioned above. This is a major effort in this work package.
- To perform measurements, using the new techniques
- To assess available and new data, for the following purposes:
    - To demonstrate the harmonised data structure
    - To demonstrate the measurement methods (this data will be used for the validation) and their consistency with the calculation tools
    - To demonstrate the classification method

Achievement of these objectives in the form of reports and proposals will be the deliverables for this Work Package.

1.3 WP 3: Consensus Building Workshops

Supporting WP's 1 and 2, a number of consensus building workshops will be organised to take account of input from Railway operators, Infrastructure management, capacity regulators, UIC/CER/UIP, legislators from EU, national authorities and local authorities, industry, UNIFE, consultants and universities.

The intention of the workshops is for the various parties to reach agreement on how to balance the environmental needs of the Community with the available technical solutions and costs for implementation within a realistic timescale. They will further establish a consensus view of the priority areas of source noise improvements.

The objectives will be to:

- Discuss the opportunities of an optimisation of rules, legislation and voluntary agreements.
- Identify initiatives aimed at:
    - Practical measures for retrofit such as composite brake blocks
    - Mix of retrofit and new design solutions
    - Specifications for future low noise trains (source noise)
    - Combination of source and abatement: bogie shrouds, low barriers
- Provide a liaison with the STAIRRS project steering group and Working Groups of EU Future Noise Policy.

2 Scientific and technical description of the results

2.1 Work Package 1

2.1.1 Summary

The decision support strategy tool was successfully developed over the three years of the project with a series of planned activities and deliverables.

Based on previous studies in Switzerland, for the UIC and in the Silent Freight/Silent Track projects the principles of what such a tool should contain were developed. These would consist of:

- A noise prediction scheme, which could quantify the noise change due to different mitigation options,
- a cost algorithm for the alternative mitigation options,
- a methodology to determine the effectiveness of different mitigation strategies and
- a methodology to compare the cost effectiveness of the different mitigation strategies

Additional elements would include extrapolation capabilities, optimisation modules and more rigorous cost and benefit studies. This latter part would be put together by partners, ULB and ETH who specialise in carrying out environmental cost and benefit studies.

Since the final tool would describe benefits in acoustic terms rather than monetary terms it is strictly a cost/effectiveness tool.

Figure 1 shows the schematic view of the Decision Support Tool and how all the elements link together.

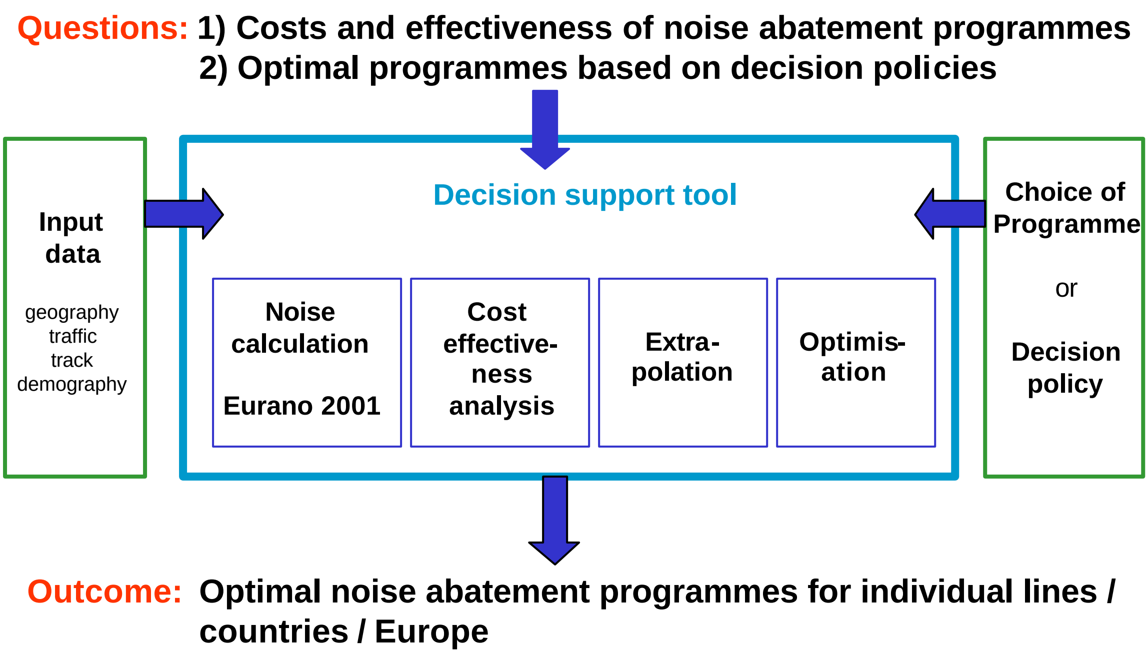


Figure 1: Decision Support Tool Concept

Detailed descriptions of the various elements are contained below.

2.1.2 Noise Calculation

2.1.2.1 EURANO 2001

Deliverable 2 of the project described the background to the EURANO 2001 software, (the software originally developed by NSTO (now AEA Technology Rail BV) and enhanced through studies for UIC), the algorithms for predicting noise reception levels and identified the system requirements for data entry and calculation (see Table 1)

Processor	Pentium II 450 Mhz (minimum) AMD Athlon 1 Ghz (recommended)
System	Windows NT 4.0 (Service pack 6) (recommended) Possibly Windows 2000
Database	MS Access 97
Memory	64 MB (minimum) 128 MB (recommended)
Video	VGA 800 x 600 64 K colours (minimum) AGP (8 MB) 1024 x 786 16M colours (recommended)
Monitor	15 "(minimum) 19 " (recommended)
Harddisk	IDE 4 GB (minimum) 6-8 GB Ultra DMA or SCSI (recommended)
Free diskspace	25 MB for its program files Approximately 1 GB for its data and calculation files About 10 GB for digital topographical maps

Table 1 System specifications.

A coding system for railway and geographic data was identified so that each partner responsible for data input could input the national data set and the data of the software system. To check the digital data before input in the software system, a consistency checker was provided which accepts the data or gives a log report with data errors.

Following data entry by the partners AEA Technology Rail BV carried out the initial noise level calculations for the whole route choice.

Noise reception calculations were made in terms of L_{den} for consistency with the latest recommendations for the European Commission on harmonised noise indictors.

L_{den} is defined by the equation

$$Lden = 10\lg\frac{1}{24}\left(12*10^{\frac{L_{day}}{10}} + 4*10^{\frac{L_{evening}+5}{10}} + 8*10^{\frac{L_{night}+10}{10}}\right)$$

in which

L_{day} is the 12 hour day, A-weighted long-term average sound level, determined over all the day periods of a year;

$L_{evening}$ is the 4 hour evening, A-weighted long-term average sound level, determined over all the evening periods of a year;

L_{night} is the 8 hour night, A- weighted long-term average sound level, determined over all night periods of a year;

To calculate noise reception EURANO 2001 uses the following noise calculation algorithms:

Noise creation:

Noise creation levels for each train type, E, are defined for a distance of 1 m from the track, assuming an acoustically absorbing ground using the following equation:

$$E_{nb,c} = a_{nb,c} + b_{nb,c} \log v_{nb,c} + 10 \log L_{nb,c} + C_{c,t}$$

where

a_c = constant which varies for different train types.

b_c = constant for the relation between train speed and noise creation which varies for different train types between 10 and 35.

L_c = total length of all trains of that type per hour (based on a reference of 1 m train per hour.

$C_{c,t}$ = correction for the track construction which varies for different train types

(subscript nb = not braking, the same formulation is used to predict the noise from braking trains using a subscript b)

Noise creation characteristics were provided for 10 Austrian train types, 6 Belgium train types, 8 French train types, 14 German train types, 8 Italian train types, 7 Swiss train types and 10 Dutch train types. Constants a, b and C were defined for each from the characteristics in the respective national noise prediction schemes.

Noise propagation

The noise propagation D contains 5 main components:

1. attenuation due to the geometrical spreading D_{geo}
2. attenuation due to the air absorption D_{air}
3. attenuation due to the ground effect D_{ground}
4. meteorological correction (i.e. down wind propagation=worst case) D_{meteo}
5. screening attenuation D_{screen}

These are effectively the algorithms used in the Dutch prediction model.

Choice of lines

In order to provide a statistically valid database of predicted noise levels a decision was required at an early stage of the project on the extent of the railway lines in Europe that would provide the basis for the data.

Although not a defined deliverable, the choice of lines used for acoustical data collection, and subsequent cost benefit analysis, was also sent to the EU for comment in June 2000. Base calculations were performed on a total length of about 11’000 km, representing about 10% of the total line length in the seven countries considered. The project’s choice of 10’974km, as defined in Table 2, was accepted as providing a representative selection of the railway lines in the countries of the participating consortium members.

Railway, Country	Length to be studied	Total network length
DB, Germany	4121 km	38'450 km
FS, Italy	1557 km	16'031 km
NS, The Netherlands	600 km	3000 km
OeBB, Austria	480 km	5627 km
SBB CFF FFS, Switzerland	576 km	2939 km
SNCB, Belgium	330 km	3422 km
SNCF, France	3310 km	31'821 km
Total	*10'974 km*	*101'290 km*

Table 2: Choice of Lines

The lines were chosen to provide a representative mix for the involved countries based on acoustic criteria such as:

noise creation levels (high, medium, low)

percentage freight traffic (high, medium, low)

population density (rural versus urban areas)

terrain (flat versus mountainous)

Not included were lines for which the 60 dB(A) contour was closer than 10 m from the track. This translated to about 2 short disc braked trains per hour or one cast iron block braked train every four hours. These types of lines do not require any measures and therefore need not be analysed.

Where possible the representative lines were connected to create European corridors.

Within the chosen lines all conceivable acoustical situations can be found. This will allow extrapolation to other networks by determining how often specific situations occur.

Figure 2 shows an overview of the chosen lines.

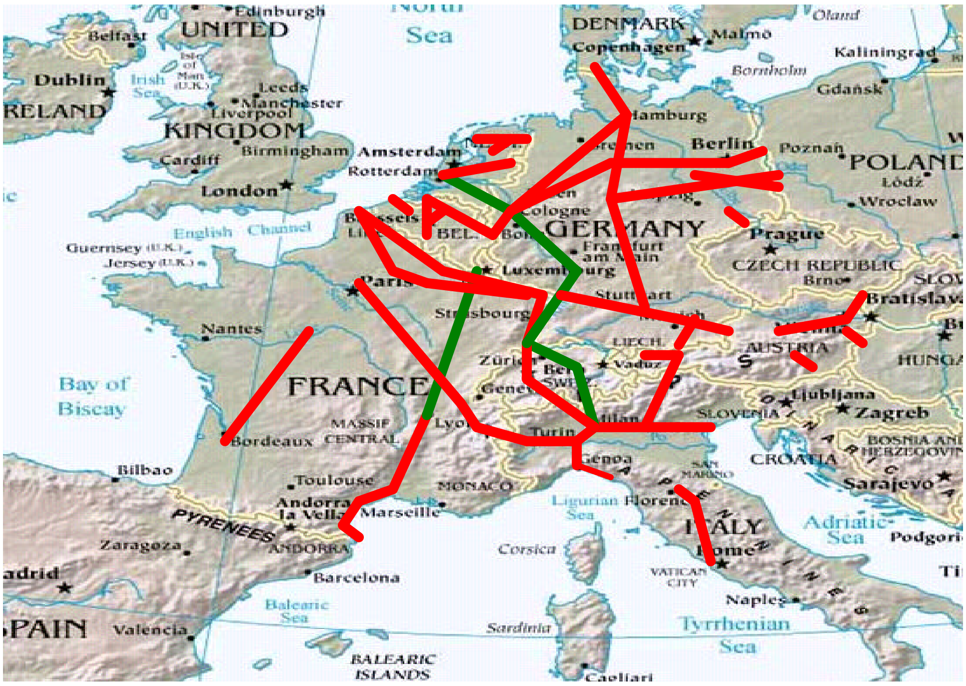


Figure 2: Overview of Choice of Lines

Training was provided for all the partners carrying out data entry for the noise calculations and the documentation for this provided Deliverable 3 of the project. This Deliverable was a working document for members of Work Package 1 and was effectively the User Guide for Eurano 2001.

It was thus possible to prepare Deliverable 4 which contained the whole data set on which the noise calculations would be made. This consisted of

- *Geographic data:* Geographic data consists of the extent of urban areas (8000) and location of individual houses (80 000) adjacent to the lines. This was determined based on maps to the scale of 1:25'000. Exceptions are Belgium, where maps 1:50'000 and Italy where maps 1:200'000 were used. In Italy, however, a quality control with maps 1:50'000 was undertaken, where such maps were available. In France the extent of the urban areas was purchased digitally from a separate organisation so that entry was not necessary.
- *Traffic data:* Traffic data consists of the number, composition and speed of trains. For the purposes of STAIRRS the data is based on prognosis values for the year 2005. If not available, current data was used. To complete the noise calculations it was necessary to assign noise characteristics a and b for all trains that would operate on the chosen lines. This consisted of determining the noise characteristics used in the relevant national prediction scheme in terms of those constants.
- *Track data:* Acoustically relevant elements of the track include type of sleeper, track condition (e.g. welded vs. non welded track) and noisy bridges. In most cases this data was available, if not, default values were used.

Figures 3 and 4, taken from the Belgium data set, show examples of the detail to which calculations were made.

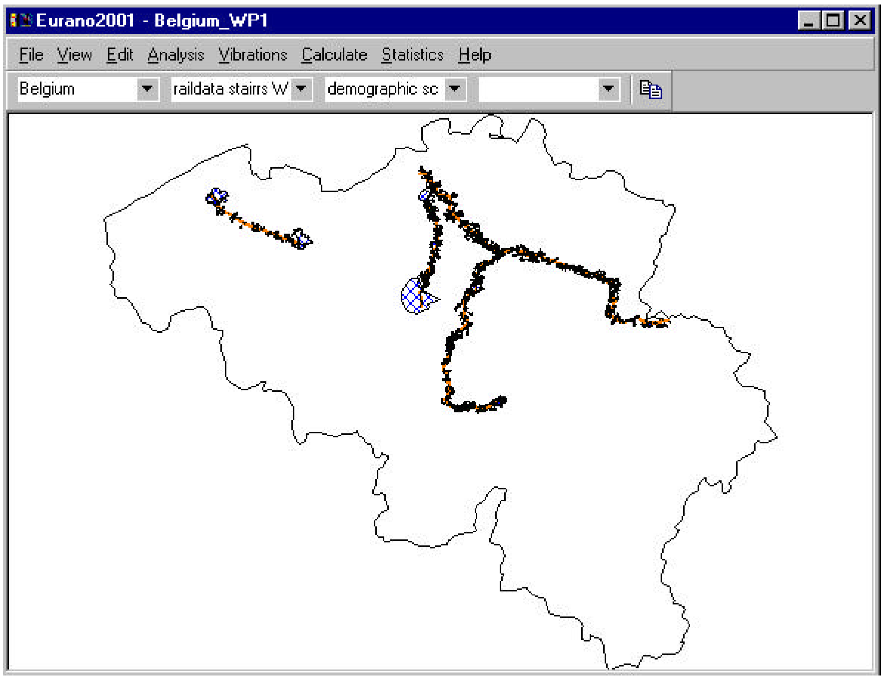


Figure 3: Choice of Lines, Belgium

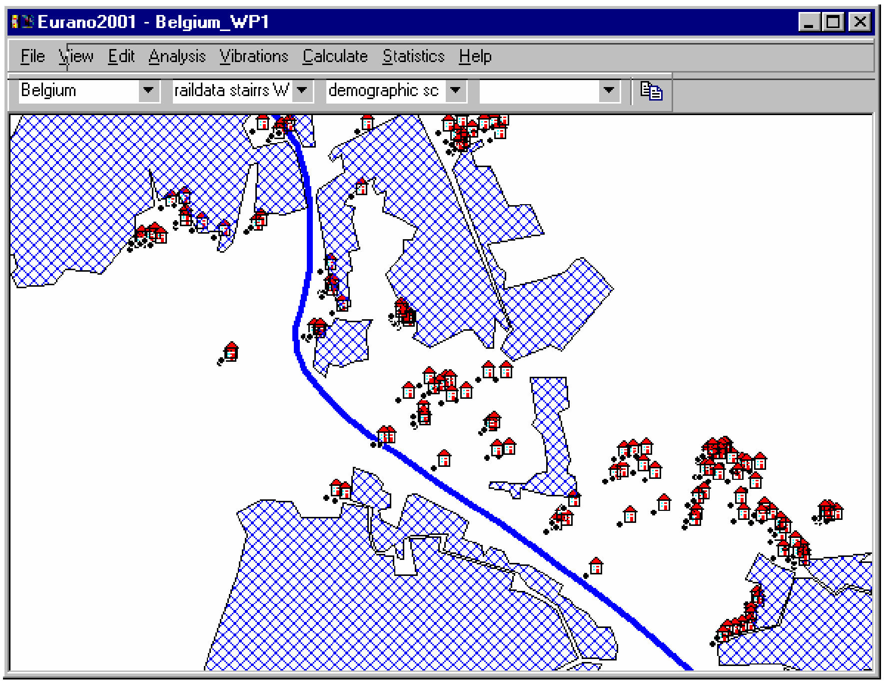


Figure 4: Detailed Geography, Belgium

2.1.3 Noise Mitigation Scenarios

In addition to the reference situation, case 0, 11 noise mitigation scenarios either singly or in combination, as summarised in Table 3, were investigated. Measures were taken either on the vehicles (global measure) or on the tracks (local measure). In situations comprising both measures, decisions on whether a local measure was necessary were taken after the noise levels were predicted for the effect of the global measure.

	Freight rolling stock			Track		Noise barriers	
	freight –10dB (A)	composite brake blocks	optimised Wheels	acoustic grinding	tuned absorbers.	2 m	max. 4 m
0							
1	XXXXX						
2		XXXXX					
3				XXXXX			
4					XXXXX		
5						XXXXX	
6							XXXXX
7		XXXXX	XXXXX		XXXXX		
8		XXXXX			XXXXX		
9		XXXXX				XXXXX	
10				XXXXX		XXXXX	
11		XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Insulated windows will be installed in all cases, in which thresholds are not attained.							

Table.3: Combinations of measures chosen. The “0” option indicates the reference situation without measures.

The analysis carried out in STAIRRS considers the reduction of rolling noise only. Total rolling noise is the sum of wheel radiated noise and track radiated noise. The balance between these sources, given in the equation below, varies with detailed design of wheel and track and operating conditions.

$$L_{TOT} = 10 \log (10^{LWHEEL/10} + 10^{LTRACK/10})$$

Where:

L_{TOT} = total rolling noise

L_{WHEEL} = wheel radiated noise

L_{TRACK} = track radiated noise

When considering noise mitigation that affects only the wheel component or the track component it is necessary to consider the contribution each makes total noise.

If $L_{WHEEL} - L_{TRACK} \geq$ 10 dB(A), wheel treatments in isolation will be more effective.

If $L_{TRACK} - L_{WHEEL} \geq$ 10 dB(A), wheel treatments in isolation will be ineffective.

Measures which affect either wheel or rail roughness will affect both the wheel and track components of rolling noise because roughness has a direct influence on the force between wheel and rail. This is the situation for scenarios 1, 2 and 3 above.

The noise reduction effect of other single measures will reduce either the vehicle component of rolling noise (global measure eg optimised wheel) or the track component of rolling noise (local measure eg rail tuned absorber). The effect of these measures on total rolling noise depends on the contribution of vehicle noise or track noise to total noise and is a function of train speed and design.

To quantify these effects a "look up" table was developed from TWINS predictions. This required input parameters of train speed, rail roughness for smooth service rails and acoustically ground rails (from published data), wheel roughness for disc braked wheels, cast iron tread braked wheels (again from published data). No data were available for the roughness of wheels with composite tread brakes and the disc braked wheel roughness was used. The roughness levels used in this study are given in Figure 5.

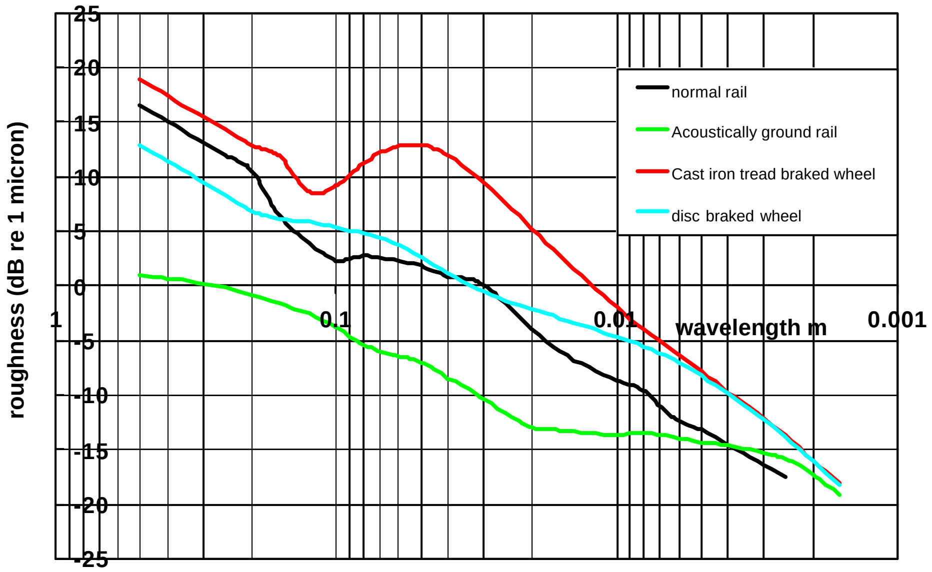


Figure 5 Roughness spectra in look up table

2.1.3.1 Summary of Noise Mitigation Scenarios and Calculation Procedure

Scenario 0 (reference)

The noise reception levels in urban areas and individual buildings for scenario 0 were calculated with standard parameters.

Scenario 1(freight - 10 dB(A))

For scenario 1 the noise from all freight trains with cast iron tread brakes is reduced by 10 dB(A).

Scenario 2 (composite brake blocks)

Installing composite brake blocks on all cast iron braked freight vehicles. Noise reduction is calculated from look up table as difference between wheels with cast iron tread braked wheels and disc braked wheels on track with normal rail.

Scenario 3 (acoustic grinding)

Acoustically optimised grinding is done longitudinally with a fine grinding stone at lower speeds and is more expensive than normal grinding.

For scenario 3 noise reception is calculated with the standard noise creation of scenario 0. Grinding is applied for each urban area where the noise reception exceeds 60 dB(A) L_{den}, and revised noise levels predicted using the reduction given in the look up table.

Comparison of roughness spectra in Figure 5 shows that the roughness of disc braked wheels is similar to the roughness of smooth rails. This means that from the data available to this project the acoustic benefit of acoustic grinding is predicted to be low. The majority of lines will also include freight with cast iron braked wheels, which will dominate the noise, particularly at night. Again because of high wheel roughness levels the effect of acoustic grinding was predicted to be low.

Scenario 4 (rail tuned absorbers)

The design of tuned rail absorbers is based on the Silent Track project and TWINS calculations have been carried out to predict the overall change in noise level for the look-up table.

For scenario 4 noise reception is calculated with the standard noise creation of scenario 0. Tuned absorbers were applied for each urban area where the noise reception exceeds 60 dB(A) L_{den} and revised noise reception levels predicted using the reduction given in the look up table.

Scenario 5 (2m noise barriers)

For scenario 5 noise reception is calculated with the standard noise creation of scenario 0. 2m high barriers were implemented for each urban area where the noise reception exceeds 60 dB(A) L_{den}. The noise reduction for barriers is predicted within the Eurano 2001software.

Scenario 6 (noise barriers up to 4m high)

For scenario 6 noise reception is calculated with the standard noise creation of scenario 0. Barriers were applied for each urban area where the noise reception level exceeds 60 dB(A) L_{den} using the following procedure:

> 60 dB(A) and < 65 dB(A)	barrier, 2 m height
> 65 dB(A) and < 70 dB(A)	barrier, 3 m height
> 70 dB(A)	barrier, 4 m height

The noise reduction for barriers is predicted within the Eurano 2001software.

Scenario 7 (composite brakes + optimised wheels + rail tuned absorbers)

Optimised wheels are those in which the shape has been modified and damping added to reduce noise. The design and performance is based on the results of the Silent Freight project and TWINS calculations have been carried out to predict the overall change in noise level for the look-up table.

Noise reduction measures are introduced as follows to produce revised noise reception levels:

- Composite brake blocks and optimised wheels are introduced on all freight trains with cast iron tread braked wheels and their effect is predicted using the look-up table.

- Rail tuned absorbers were then applied for each urban area where the noise reception level exceeds 60 dB(A) L_{den}. The effect of this change is predicted from the data in the look-up table to give revised noise reception levels.

Scenario 8 (composite brakes + rail tuned absorbers)

For scenario 8 noise reception levels for scenario 2 (composite brake blocks) are used. Rail tuned absorbers are then applied for each urban area where the noise reception level exceeds 60 dB(A) L_{den}. The effect of this change is predicted from the data in the look-up table to give revised noise reception levels.

Scenario 9 (composite brakes + 2m noise barriers)

For scenario 9 again the noise reception levels for scenario 2 were used. 2m high noise barriers are applied in each urban area where the noise reception level exceeds 60 dB(A) L_{den} to give revised noise reception levels.

Scenario 10 (acoustic grinding + 2m noise barriers)

For scenario 10 the reference noise creation of scenario 0 was used. Noise reduction measures are introduced as follows to produce revised noise reception levels:

- rail grinding is applied for each urban area where the noise reception level exceeds 60 dB(A) L_{den}. A new noise reception level is calculated using data from the look-up table for the effects of acoustic grinding.
- 2m high noise barriers are applied for each urban area where the noise reception level still exceeds 60 dB(A) L_{den} to give revised noise reception levels.

Scenario 11 (composite brakes + optimised wheels + rail tuned absorbers + acoustic rail grinding + 2m barriers)

For scenario 11 the noise creation of scenario 7 was used.

Additional noise reduction measures were introduced as follows:

- rail grinding was applied for each urban area where the noise reception level exceeds 60 dB(A) L_{den}. A new noise reception level is calculated using data from the look-up table for the effects of acoustic grinding.
- 2m high noise barriers are applied for each urban area where the noise reception level still exceeds 60 dB(A) L_{den} after grinding to give revised noise reception levels.

It should be noted that the combinations of measures did not include rerouting or operational measures (in particular changes in speeds). The STAIRRS consensus building workshops indicated that both measures are not consistent with the requirements of a commercially viable railway.

2.1.4 Cost Effectiveness Functions

2.1.4.1 Background

The objective of this part of the project was to develop cost and benefit functions to assess and compare the noise reduction scenarios described in 2.1.3.

Benefits could be calculated based on three alternative measures:

- the reduction in the number of people encountering more than 60dB(A) L_{den},
- reduction in the number of people annoyed by noise and

- reduction in the number of people weighted by their noise reception levels.

The majority of analysis compares benefits in terms of reduction in number of people with noise level greater than 60 dB(A) L_{den}.

As previously described these benefits result from the introduction of global measures to vehicles and local measures taken on the track in urban areas.

It is not possible to apply all these measures instantly or even at the same moment in time therefore the assessment takes into consideration different options for phasing the mitigation work. Overall this gave rise to the assessment of 20 investment programmes. The costs and benefits for each of these programmes was assessed using a short term approach and a long term approach as defined below:

- *Short-term approach:* Different noise control strategies (for example consisting of varying combinations of noise control measures) are compared based on investment costs. These measures have a benefit during their lifetime only. This approach implies that technological advances will progress during the lifetime of the products thus requiring an analysis and a new decision at the end of their lifetimes. This approach therefore does not include costs to replace measures.
- *Long-term approach*: This approach assumes that noise target values must be attained over long periods of time. This requires replacement of noise measures at the end of their lifetime so that these costs are included. The costs and benefits are assessed for a perpetual noise abatement. This approach uses the econometric formula for perpetual annuities.

Both approaches compare costs using net present values, the benefits however are defined in physical terms (i.e. noise reduction per lineside inhabitant) and are called “effectiveness”. The study is therefore a cost-effectiveness approach. The ratio between the physical benefit function and the cost function is called “efficiency”.

2.1.4.2 Definitions

Measure: A technical possibility for reducing noise and their impact eg noise barriers or new wagons

Scenario: a combination of measures to mitigate noise

Programme: A combination of measures with their implementation schedule. (a maximum implementation period of 10 years was used in STAIRRS)

Benefit: Improvement in noise situation for lineside inhabitants expressed in monetary terms.

Effectiveness: Physical, non monetary “benefits” of a measure.

Efficiency: Ratio of effectiveness and costs.

The cost function: For the short term approach, the cost function is the sum of all investment, maintenance and removal costs for a programme, until the end of the modelling period. The investment costs are summed for each measure implemented during the 10-year investment programme. The maintenance costs are added for each measure and each year from the start of maintenance to the end of the lifetime of the measure. Removal costs occur at the end of the lifetime for those measures that must be removed (e.g. noise barriers). All costs are discounted to the first year of the programme.

The effectiveness function: The present benefit function expresses the effectiveness as the reduction of annoyed persons or of persons with noise reception values above 60 dB(A) L_{den}

multiplied by the number of years during which this reduction lasts (persons no longer above 60 dB(A) L_{den} * years). This unit gives a total effectiveness for a definite number of years.

***Discount factor*:**

The effects of noise and noise reduction reach far into the future and the costs can be planned for the next years. This makes it necessary to discount costs. The net present value of a future investment (such as in 10 years) is lower than its exact value for a number of reasons.

1. A certain amount of money can be invested now and an interest rate obtained, which increases the capital invested. Therefore the amount of money, which is needed today is less than what will be needed in 10 years. With this money a public investor can finance public debts and achieve considerable interest rates.
2. Future investments might be cheaper due to an increase in technology and productivity.
3. Inflation might increase the cost of implementing the same measure in the future compared to today and decrease the value of future investments.

Similarly the effectiveness of noise reduction measures has to be discounted. Firstly, because effectiveness and costs should be discounted at the same rate, secondly because of the preference for current noise reduction over future noise reduction, and thirdly because new noise reduction technologies may emerge which might be preferred to the current options.

Discounting consists of dividing the cost occurring at year t by $(1+r_c)^{(t-1)}$, and the effectiveness occurring at year t by $(1+r_b)^{(t-1)}$.

The rate of cost discounting, r_c, is assumed to be uniform for all countries modelled in STAIRRS. A rate of 5% has been chosen, which is based on current practice throughout Europe. The rate of benefit discounting, r_b, is assumed to be equal to r_c.

2.1.4.3 Basic Cost Data

Tables 4 and 5 give the cost data used in STAIRRS and their source. Maximum and minimum costs were used in sensitivity analyses.

Parameters — **Average Costs**

Parameters	units	Noise barriers 2m	Noise barriers 3m	Noise barriers 4m	Insulated windows per house 4 windows*	Rolling stock improvement (freight cars) Brakes 1	Rolling stock improvement (freight cars) Brakes 2	Rolling stock improvement (freight cars) Optimised wheels	Rolling stock improvement (passengers cars) Brakes 1	Rolling stock improvement (passengers cars) Brakes 2	Rolling stock improvement (passengers cars) Optimised wheels	Track improvement Tuned Absorbers	Track improvement Grinding**	
Measure No		1	2	3	4	5	6	7	8	9	10	11	12	
Investment cost per unit, I	€	933.00	1'215.00	1'475.00	5'600.00	9'881.00	4'996.19	11'557.88	0.00	0.00	0.00	500.00	0.00	
Lifetime per measure, T_L	Years	25	25	25	80	40	40	10	40	40	10	30	80	
Start of maintenance, t_M	Years	1	1	1	1	1	1	1	1	1	1	1	1	
Frequency of maintenance, t_{Mp}	Years	1	1	1	1	1	1	1	1	1	1	1	5	
Maintenance costs, M	€	18.66	24.30	29.50	0.00	0.00	0.00	231.16	0.00	0.00	0.00	10.00	10.32	
Maintenance part	%	2%	2%	2%	0%	0%	0%	2%	0%	0%	2%	2%		2%
Removal costs, R	€	93.30	121.50	147.50	0.00	494.05	249.81	0.00	0.00	0.00	0.00	50.00	0.00	
Removal part	%	10%	10%	10%	0%	5%	5%	0%	5%	5%	0%	10%	0%	10%
p-rate		2.39	2.39	2.39	48.56	6.04	6.04	0.63	6.04	6.04	0.63	3.32	48.56	

discount / interest rate (r_c):	0.05	rate of cost discounting
Present preference interest rate (r_b):	0.05	rate of benefit discounting

Parameters — **Minimum Costs**

Parameters	units	Noise barriers 2m	Noise barriers 3m	Noise barriers 4m	Insulated windows per house 4 windows*	Rolling stock improvement (freight cars) Brakes 1	Rolling stock improvement (freight cars) Brakes 2	Rolling stock improvement (freight cars) Optimised wheels	Rolling stock improvement (passengers cars) Brakes 1	Rolling stock improvement (passengers cars) Brakes 2	Rolling stock improvement (passengers cars) Optimised wheels	Track improvement Tuned Absorbers	Track improvement Grinding**	
Measure No		1	2	3	4	5	6	7	8	9	10	11	12	
Investment cost per unit, I	€	600.00	1'080.00	1'350.00	2'200.00	9'881.00	3'756.00	11'557.88	0.00	0.00	0.00	500.00	0.00	
Lifetime per measure, T_L	Years	25	25	25	80	40	40	10	40	40	10	30	80	
Start of maintenance, t_M	Years	1	1	1	1	1	1	1	1	1	1	1	1	
Frequency of maintenance, t_{Mp}	Years	1	1	1	1	1	1	1	1	1	1	1	5	
Maintenance costs, M	€	12.00	21.60	27.00	0.00	0.00	0.00	231.16	0.00	0.00	0.00	10.00	6.40	
Maintenance part	%	2%	2%	2%	0%	0%	0%	2%	0%	0%	2%	2%		2%
Removal costs, R	€	60.00	108.00	135.00	0.00	494.05	187.80	0.00	0.00	0.00	0.00	50.00	0.00	
Removal part	%	10%	10%	10%	0%	5%	5%	0%	5%	5%	0%	10%	0%	10%
p-rate		2.39	2.39	2.39	48.56	6.04	6.04	0.63	6.04	6.04	0.63	3.32	48.56	

discount / interest rate (r_c):	0.05	rate of cost discounting
Present preference interest rate (r_b):	0.05	rate of benefit discounting

Parameters — **Maximum Costs**

Parameters	units	Noise barriers 2m	Noise barriers 3m	Noise barriers 4m	Insulated windows per house 4 windows*	Rolling stock improvement (freight cars) Brakes 1	Rolling stock improvement (freight cars) Brakes 2	Rolling stock improvement (freight cars) Optimised wheels	Rolling stock improvement (passengers cars) Brakes 1	Rolling stock improvement (passengers cars) Brakes 2	Rolling stock improvement (passengers cars) Optimised wheels	Track improvement Tuned Absorbers	Track improvement Grinding**	
Measure No		1	2	3	4	5	6	7	8	9	10	11	12	
Investment cost per unit, I	€	1'220.00	1'350.00	1'600.00	8'000.00	9'881.00	9'881.00	11'557.88	0.00	0.00	0.00	500.00	0.00	
Lifetime per measure, T_L	Years	25	25	25	80	40	40	10	40	40	10	30	80	
Start of maintenance, t_M	Years	1	1	1	1	1	1	1	1	1	1	1	1	
Frequency of maintenance, t_{Mp}	Years	1	1	1	1	1	1	1	1	1	1	1	5	
Maintenance costs, M	€	24.40	27.00	32.00	0.00	0.00	0.00	231.16	0.00	0.00	0.00	10.00	14.00	
Maintenance part	%	2%	2%	2%	0%	0%	0%	2%	0%	0%	2%	2%		2%
Removal costs, R	€	122.00	135.00	160.00	0.00	494.05	494.05	0.00	0.00	0.00	0.00	50.00	0.00	
Removal part	%	10%	10%	10%	0%	5%	5%	0%	5%	5%	0%	10%	0%	10%
p-rate		2.39	2.39	2.39	48.56	6.04	6.04	0.63	6.04	6.04	0.63	3.32	48.56	

discount / interest rate (r_c):	0.05	rate of cost discounting
Present preference interest rate (r_b):	0.05	rate of benefit discounting

Note: * We consider no maintenance costs for insulated windows.
** Grinding is taken into account as maintenance costs.
Please use real costs (not nominal).

Table 4: Basic costs used in STAIRRS.

Measure	Eurano dataset	Extrapolation to 21 countries	Individual countries
Freight rolling stock improvement, number of wagons	number of wagons are 10 % of total number for the countries A,B,CH,D,F,I,NL	a) UIC action programme freight noise reduction number for the 21 countries b) total number of wagons in the 21 countries	Total number of wagons registered in that country (based on UIC statistics)
Freight –10 dB	Maximum price found	maximum price found	maximum price found
Composite brake blocks	average price from UIC action programme freight noise reduction, sensitivity with minimum and maximum	average price from UIC action programme freight noise reduction, sensitivity with minimum and maximum	average price from UIC action programme freight noise reduction
Optimised wheel	costs from SNCF	costs from SNCF	costs from SNCF
Noise barriers	average taken from different sources, sensitivity with minimum and maximum costs	average taken from different sources, length based on extrapolation, sensitivity with minimum and maximum costs	average taken from different sources, length based on extrapolation
Tuned rail absorbers	costs from SNCF, sensitivity with minimum and maximum costs	cost from SNCF, length based on extrapolation, sensitivity with minimum and maximum costs	cost from SNCF, length based on extrapolation
Acoustic grinding	average taken from different sources	average taken from different sources	average taken from different sources, length based on extrapolation
Insulated Windows	average taken from different sources, sensitivity with minimum and maximum costs	average taken from different sources, length based on extrapolation, sensitivity with minimum and maximum costs	average taken from different sources, length based on extrapolation

Table 5: Major assumptions used to determine costs.

2.1.4.4 Effectiveness Functions

Short-term Approach

The Present Benefit (*PB*) function (expressed in physical terms) is the sum of the basic effectiveness, B_t, calculated and discounted for each year of the period modelled (from t=1 to the end of the period modelled, t_{end}).

It is assumed that as the result of regular maintenance, a given number of units provide a constant level of effectiveness in terms of noise reduction throughout their lifetime.

The time factor has to be included in the weighting of the effectiveness. In the short-term approach, this is done by assessing the effectiveness for each year of modelling, from the first year to the end of the lifetimes of the measures (t_{end}). A table of cumulated units of the measures during this whole period is used. This table is based on the investment programme and the lifetime of each measure. It gives the actual number of units of each measure effectively in use during each year of the period modelled. The effectiveness of each single measure ($B_{t,\,m}$) and of some of the interactions ($B_{t,\,int\,m1m2}$) is calculated for each year t of the modelling with the cumulated units of the measures involved.

The effectiveness is then discounted from the year at which it occurs (t) to the so-called "present year" (first year of the programme). Indeed, the perception of noise levels is not linear over time and people are assumed to prefer an early reduction of noise.

The rate of benefit discounting (r_b) may vary depending on the weight that the user wants to give to the time of effectiveness emergence. In this study, it is assumed to be equal to the rate of cost discounting, r_c.

Eventually, the benefit function is :

$$PB = \sum_{t=1}^{t_{end}} \frac{(\sum_{m=1}^{n_m} B_{t,m}) + (\sum_{Interactions} B_{t,Intm_1m_2})}{(1+r_b)^{(t-1)}}$$

The Present Benefit function expresses effectiveness as the reduction of the number of people [*annoyed / weighted with f / above 60dB*] multiplied by the number of years over which this reduction lasts [people * years]. This unit gives a total effectiveness for a definite number of years (which corresponds to t_{end}). The costs are also expressed as overall costs for the same period. It is therefore a valid unit to calculate the efficiency of a programme, which is the ratio between effectiveness and costs.

Moreover, this assessment is a first step of a cost-benefit analysis with the benefits expressed in monetary units. The benefits in physical units (i.e. the effectiveness) have therefore to be compatible to monetizing. A cost would be expressed per year for one person annoyed (1 annoyed person = x € / year). The effectiveness could then be easily converted into Euros (1 annoyed person * year = x €).

Further study is needed to achieve this monetizing, which could be based on the contingent valuation method (INFRAS, 2000) or on the Hedonic Price Method (Favrel et al., 2001).

Long-term approach

The Perpetual Present Benefit (*PPB*) function (expressed in physical terms) is the sum of the basic benefits (B_t), calculated and discounted for each year of the period modelled, which here extends from t=1 to infinity. Because it is necessary for the Perpetual Present Benefit (*PPB*) itself not to equal infinity, the discounting is essential and a rate of benefit discounting $r_b>0$ is necessary (and sufficient).

The first reason for the development of the long-term approach is that the benefits (and also the costs, see below) have to be accounted for over a long period. The general environmental impacts of the railways and the specific noise impacts do not stop after the lifetime of a measure. This kind of thought is also relevant when trying to approach sustainability. The second reason is to come up with an evaluation which accounts for the different lifetimes of the measures. For example, a noise barrier with a lifetime of 25 years cannot be compared to a rolling stock measure with a lifetime of 40 years. Considering two noise barriers lifetimes would not be adequate either, when the end of the modelled period is 40 years because of the lifetime of a rolling stock measure. The solution to the problem of finding an appropriate time frame could be to choose the lowest common multiple (LCM) of the lifetimes of all the measures. This would be 4200 years considering the lifetimes of 25, 30, 35, and 40 years. As the reader will concede, that this approaches infinity, a long-term approach seems valuable, when it gives a generally applicable and simplifying formula. This reason similarly holds good for the cost evaluation and it should be kept in mind that the assessment of benefits and costs should be conducted within the same time-frame.

As in the short-term approach, it is assumed that as the result of regular maintenance, a given number of units of a measure provides a constant benefit in terms of noise reduction throughout its lifetime. Moreover, the long-term approach assumes that at the end of the lifetime of a measure, it is not only removed (as in the short term approach), but also replaced, so that the benefits are continuous.

The general conclusions from cost effectiveness analysis using both approaches are the same and show the same general ranking of the mitigation options.

Differences include:

- Overall discounted costs are higher in the long term approach when compared to the short term, due to replacement costs.
- Relative to the other measures, noise barriers show higher effectiveness in the long-term approach than in the short term approach. The shorter lifetime of noise barriers (25 years, compared to 30 years for tuned absorbers and 40 years for freight improvement) seems to be a disadvantage under the short-term approach, because here effectiveness is counted in persons multiplied by lifetime, unlike the long-term approach where lifetime has no influence on the effectiveness.

2.1.4.5 Cost and Effectiveness Spreadsheet

An Excel Spreadsheet has been created to implement the cost and effectiveness functions. Several sheets have been drawn up. Some of them are specifically designed to interface with the users, whereas others are only used for the calculations.
This spreadsheet calculates the costs, the effectiveness and the efficiency of a definite noise reduction investment programme. The major inputs are number of units of the annually implemented measures, i.e. the 10-year investment programme, the effectiveness of the scenarios calculated on the basis of EURANO and the parameters concerning the measures implemented (costs and lifetime).

Some functions in this spreadsheet are based on the programming language 'Visual Basic for Applications'. The objects of these functions are:

- For the short-term approach: the calculation of the end of the modelling ("tend_measure"), the cumulated number of units of the measures ("Accrued_units"), the discounted maintenance ("Discount_Maintenance").
- For the long-term approach: the calculation of the discount factor ("df"), the present value interest factor of an annuity (pvifa), the time-of-investment costs ("toi_costs") and the perpetual costs ("perpetual_costs").
- For the calculation of short-term and long-term effectiveness : the interpolation for local and global measures ("Int_localMeasure" and "Int_globalMeasure"), the interactions between the selected measures ("Int_Interaction") and the choice of the scenario to calculate ("CalculateScenario").

This spreadsheet is available on the following url:
http://www.ulb.ac.be/ceese/ACTIVITY/english/stairrs.htm

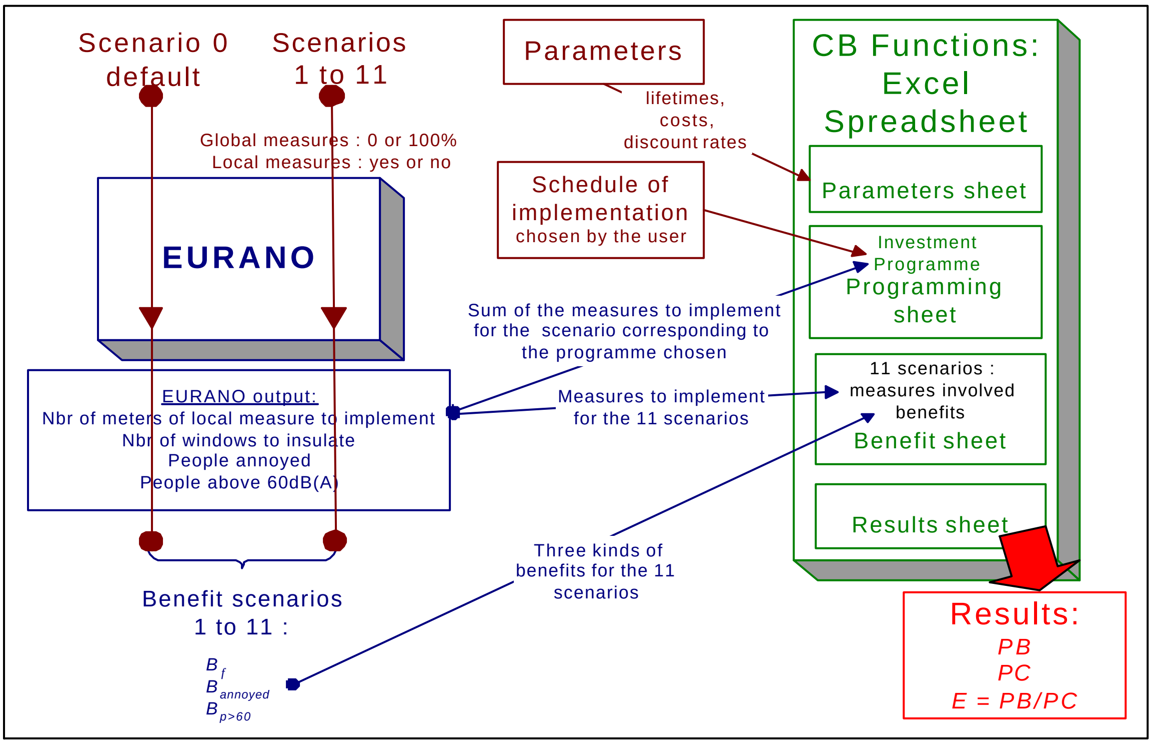


Figure 6 Data flow between EURANO and the "C B Functions" Spreadsheet.

2.1.4.6 Examples of Cost Effectiveness Calculations

Figures 7 and 8 compare the discounted costs and effectiveness of the 11 mitigation options for the Eurano area using the short term approach without allowance for insulated windows (Figure 7) and with insulated windows (Figure 8)

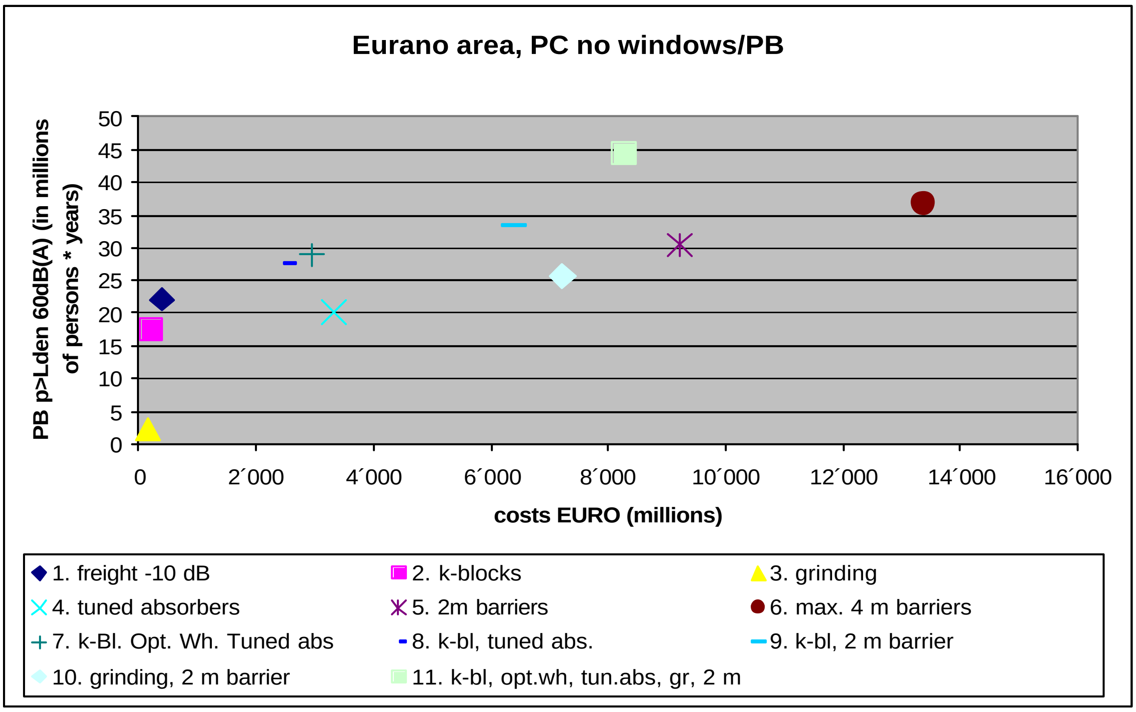


Figure 7: Discounted costs and effectiveness for Eurano area using short term approach, excluding cost of insulated windows

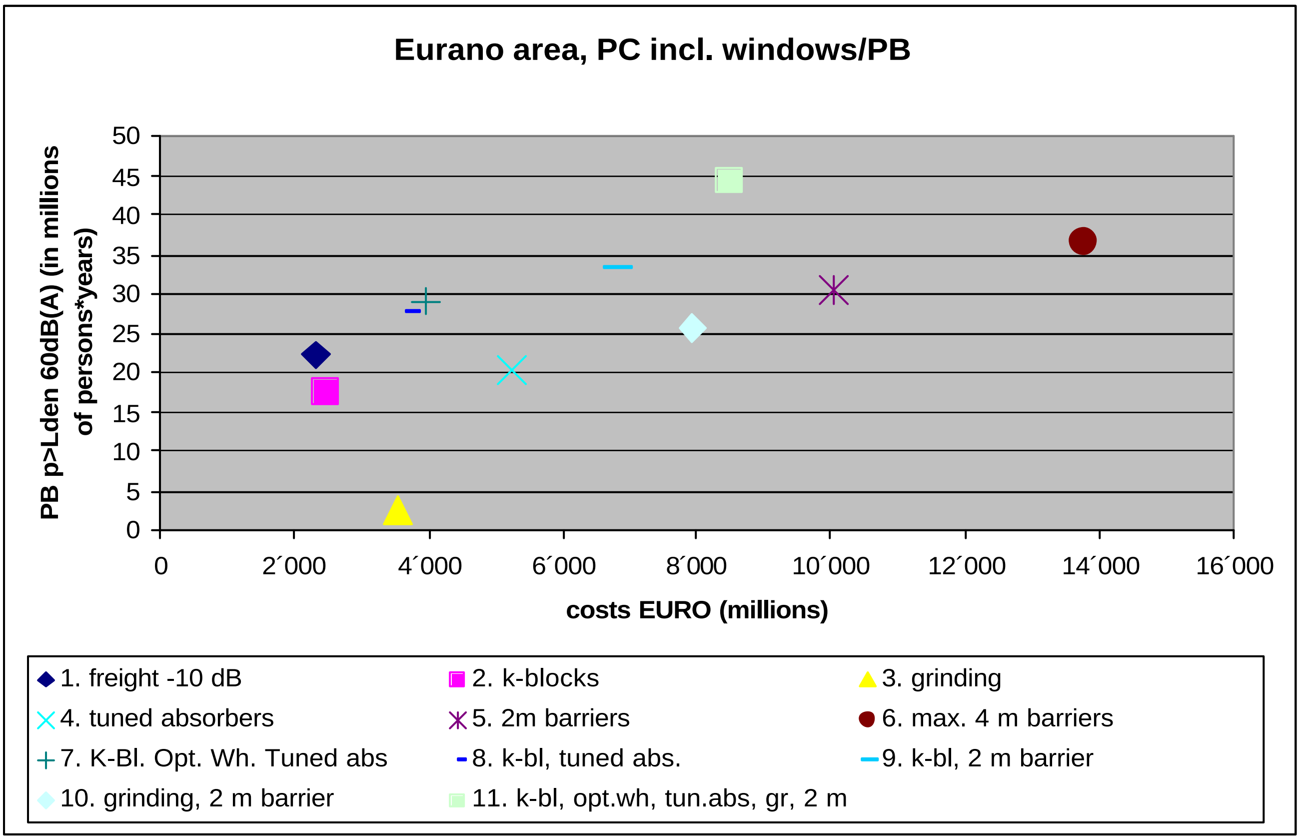


Figure 8: Discounted costs and effectiveness for Eurano area using short term approach, including cost of insulated windows

There is no change in the relative efficiency of the different mitigation options even when insulated windows are installed at properties where the noise is greater than 60 dB(A) L_{den} is included or not.

There is a high cost for window insulation in situations with low effectiveness. In the programmes with lower benefits (acoustic grinding, rolling stock improvement) this additional cost is higher than in those cases with higher benefits. For composite brake blocks, for example, the additional costs for windows raises the overall price by a factor of more than 12, while for the solution with the greatest benefit (combination of k-blocks, optimised wheels, tuned rail absorbers, 2 m barriers) the price including windows is only 1.03 times higher.

2.1.5 Extrapolation

2.1.5.1 Concept

The extrapolation methodology was developed to determine optimum noise control strategies for any geographic area of interest, be it Europe as a whole, the E.U. or an individual country. Within the choice of lines (=Eurano Area) - the 11'000 km of line length for which detailed acoustical data is available - acoustical line segments were defined. These consist of segments similar in terms of traffic and population characteristics. As a next step, the proportion of these line segments was determined in the geographic area of interest. Following that, a representative data base was chosen out of the line choice with the same proportion of acoustical line segments as in the area of interest. Noise calculations and determination of the extent of required measures were undertaken on this representative data base and were subsequently extrapolated by the ratio between line lengths in the area of interest and in the representative data base. Cost-effectiveness calculations are performed on the extrapolated data.

2.1.5.2 Extrapolation procedure

The steps used in the extrapolation procedure are:

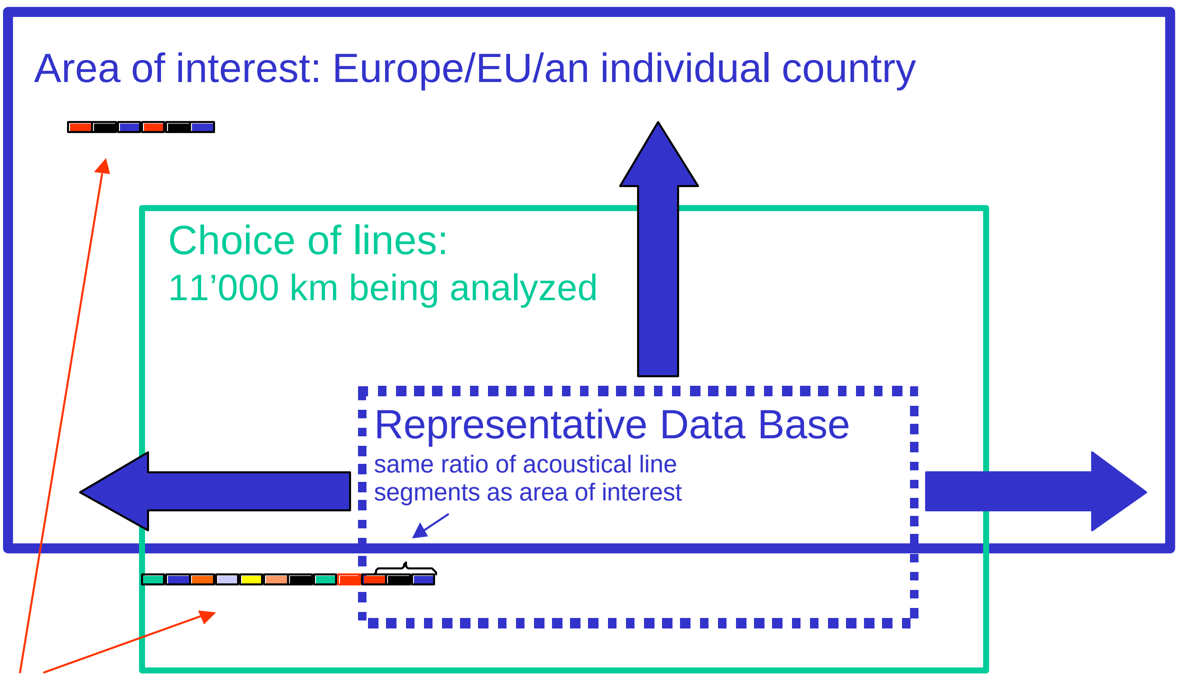
A. Acoustical line segments: The acoustical line segments are based on traffic and population criteria. The data used are the 11'000 km of detailed acoustical data as collected for the choice of lines. The necessary methodology is described in Section *2.1.5.3. Definition of typical acoustical line segments.*

B. Combination of acoustical line segments in area of interest: Based on approximate acoustic data, the combination of different acoustical line segments is determined in the area of interest. This step is described in greater detail in Section *2.1.5.4. Data collection*.

C. Representative data base: The representative data base is defined by choosing the maximum line length from choice of lines with the same proportion of acoustical line segments as in area of interest. This step can be carried out automatically with Eurano. The methodology is described in Section *2.1.5.5. Representative data base.*

D. Cost-effectiveness analysis in representative data base: All noise, cost and effectiveness calculations are undertaken on the representative data base. Basis for the noise calculations is Eurano and for the cost-effectiveness calculations are Excel spreadsheets. See *Deliverable D5, Software System for Cost-Benefit Calculations.*

E. Extrapolate to area of interest: The results from the cost-benefit analysis in the representative data base are extrapolated to the area of interest with a simple factor (line length in area of interest / line length in representative data base).



acoustical line segments

Figure 9: Extrapolation procedure.

2.1.5.3 Definition of typical acoustical line segments

Acoustical line segments are automatically generated by Eurano 2001 and are defined by the following criteria:

Population density

High population density: More than 400 persons per 1 km length x 200 m depth on each side of track. This figure is equal to a density of 2000 persons per km^2.
Low population density: Less than 400 persons per 1 km length x 200 m depth on each side of track.

Calculation methodology: This step is calculated per km and individually for each side of the track. The number of persons is calculated by Eurano 2001 based on average European urban population densities (5000 persons/km^2). Adjoining segments with the same density were connected.

Percentage of freight traffic

High: above 50 %
Low: below 50 %

Rationale: The available data from the UIC distinguishes four different categories: 0 - 25 %, 25 - 50 %, 50 - 75 % and 75 - 100%. To enable extrapolation, the limit must be at one of these values. The percentage of freight traffic varies strongly in different countries, but throughout Europe a 50 % limit will allow the most equal distribution.

Calculation: Individual railways defined categories to be considered as freight. The percentage is calculated based on train lengths.

Number of trains

High: above 100 trains per day
Low: below 100 trains per day

Rationale: The available data from the UIC distinguishes four different categories: 0 - 50, 50 - 100, 100 - 200, and 200 - 500. To enable extrapolation, the limit must be at one of these values. Roughly speaking, a boundary of 100 distinguishes between medium and high noise creation, while 200 distinguishes between high and very high noise creation. The lower distinction seems more plausible.

Calculation: Where information was available, number of trains per day is calculated by Eurano 2001. Where not, an average train length for each category was defined and number of trains determined from available train length data.

High speed lines

Yes: Line is considered a high speed line.
No: Line is not considered a high speed line.

The individual railways indicated which lines could be considered as high speed.

2.1.5.4 Data collection

Choice of lines: The collection of the detailed acoustical data is described in *Deliverable D4: Complete data set for the countries A, B, CH, D, F, I, NL by AEAT and SBB.*

Area of interest: In the areas of interest the approximate acoustic data was collected in the following way:

- **Population density**: An estimate was made using maps to the scale of 1:200'000 to 1:350'000, depending on availability. This required a visual analysis of maps in which the ratio of built up areas along lines (black) to rural areas (white) was estimated. This was done separately for each line for which train data fom the UIC was available. It was assumed that the UIC covers the important and thus most likely the noisy lines.
- **Percentage freight traffic and number of trains:** This data was obtained from the UIC.
- **High speed lines**: The information on which lines are considered high-speed was obtained from the individual railways.

The lines chosen for the approximate acoustic data collection were those for which train data was available from the UIC. It was assumed that these lines correspond to the major lines of the country.

country	***line length for approximate data collection in km***	***total line length in country in km***
Austria	1964	5568
Belgium	1617	3471
Czech Republic	921	9365
Denmark	2008	2047
Finland	1236	5854
France	6092	32515
Germany	9118	36588
Hungary	2080	7768
Ireland	934	1909
Italy	7052	16147
Luxembourg	181	274
Netherlands	1760	2802
Norway	1716	4179
Poland	6309	22891
Portugal	1424	2813
Slovakia	898	3665
Slovenia	581	1202
Spain	3211	12310
Sweden	2746	10799
Switzerland	1724	5035
United Kingdom	4869	17064

Table 6: Line length for which approximate acoustic data was collected.

This corresponds to the line length for which traffic data was available from the UIC. Line lengths of the network are from UIC statistics (International Railway Statistics, 1999).

2.1.5.5 Representative database

In each area of interest the proportion of each acoustical line segment (= specific combination of factors described above) was determined. The representative data base was subsequently chosen out of the "choice of lines". It consists of those lines which have the same ratio of acoustical line segments. This is done with a multidimensional vector analysis, in which by trial and error different vectors are tested until a predefined error threshold is achieved. The multiplication factor is determined by the ratio of line length in the representative data base and in the area of interest. An example of the iteration process based on a simplified example of two different acoustical line segments is shown in figure 10.

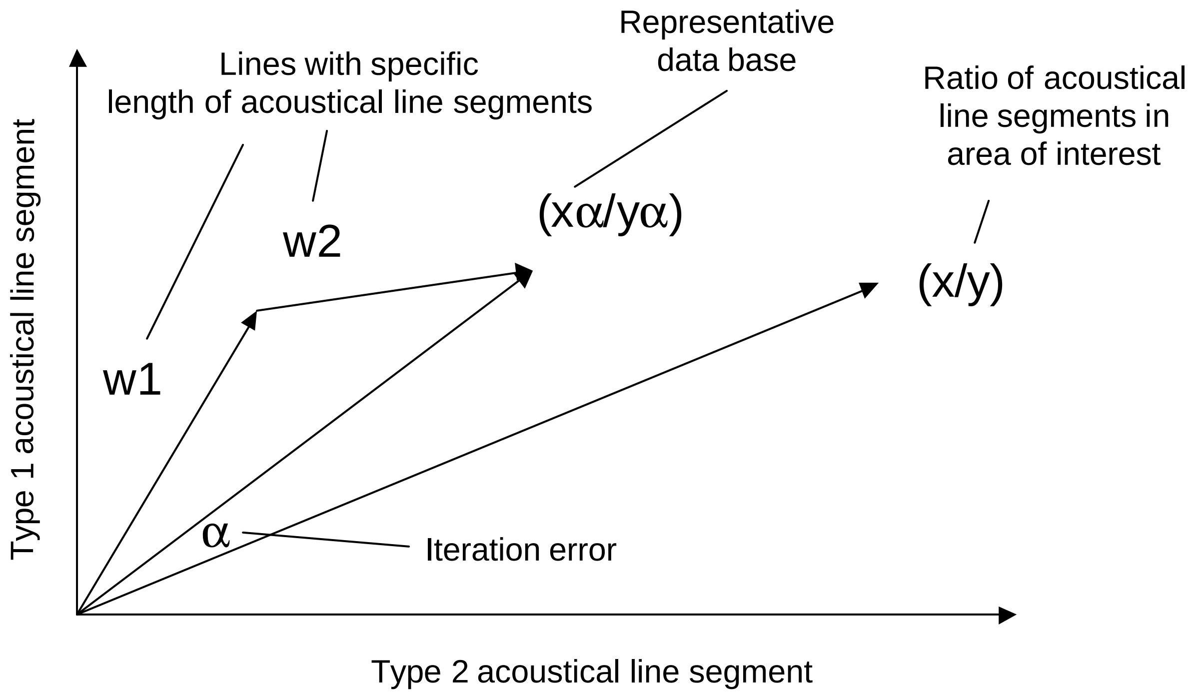


Figure 10: Illustration of iteration process to find representative data base.

The example is based on two acoustical line segments (type 1 and 2, a type is a particular combination of characteristics, e.g. high population density, high number of trains, low freight traffic). Step 1: Determine ratio of acoustical line segments in area of interest (x/y). Step 2: Try different lines until iteration error is below given value (xα/yα). w1 and w2 are lines composed of different ratios of acoustical line segments.

2.1.5.6 Geographical areas of interest

Outside the choice of lines approximate acoustical data was collected for all EU countries excluding Greece (because no reliable train data could be found for this country) plus Norway, Switzerland, Poland, Czech Republic, Slovakia, Hungary and Slovenia. This allows studies to be undertaken for each individual country, for the EU and for an extension thereof. The current data set contains data from a total of 21 different countries to which results can be extrapolated.

Figure 11 shows the results of the cost effectiveness analysis for Europe based on the extrapolation procedure.

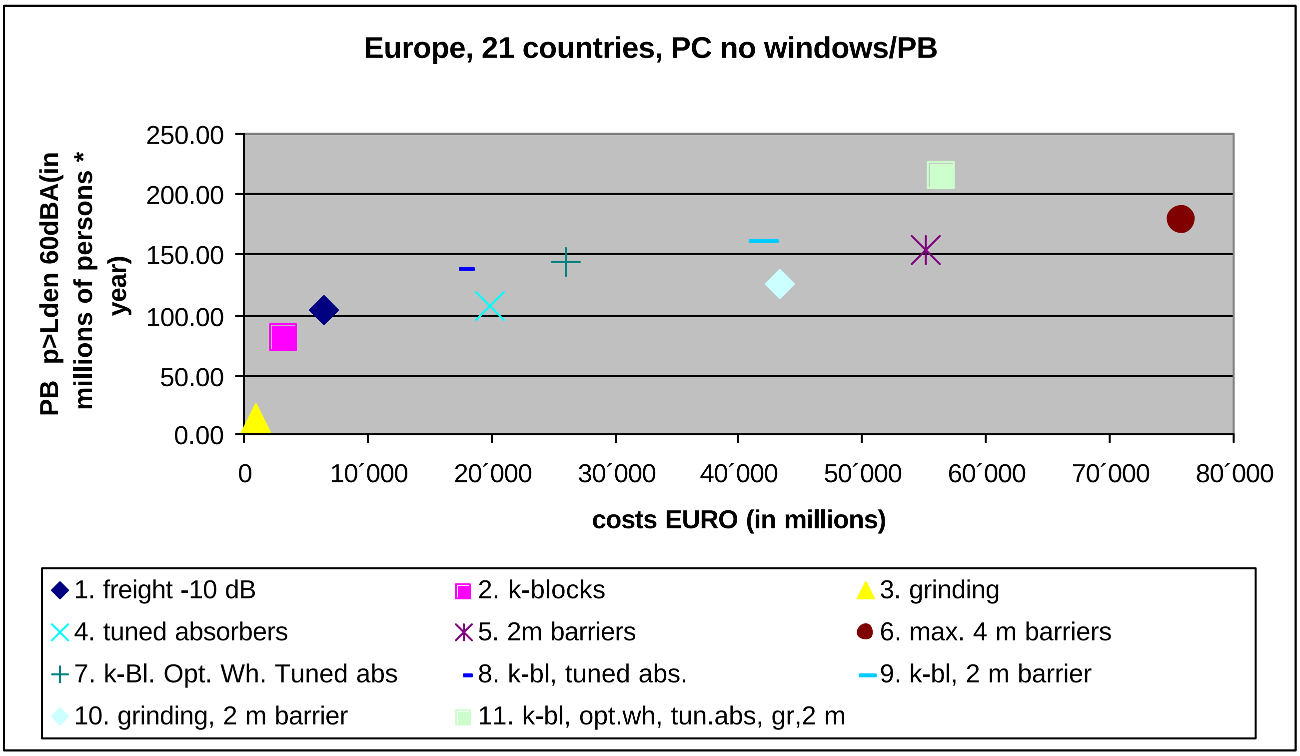


Figure 11: Discounted costs and effectiveness for 21 European countries area using short term approach, excluding cost of insulated windows

2.1.5.7 Accuracy of extrapolation

It must be noted that the extrapolation mechanism only allows very approximate information for each country. The reasons are:

- To determine the extent of urban areas maps to the scale of 1:200'000 to 1:350'000 were used. No similar maps were available for all countries, so that differences in map quality may influence results.
- Categories of traffic data are very approximate. The number of trains and the percentage of freight traffic were divided into two categories each. A small change on a long line may strongly affect the outcome in a given country.
- Only high and regular speeds were distinguished. Within the category "regular speed" differences in speeds may affect the outcome.
- Urban population densities vary between countries and within a country. In Eurano an average of 5000 persons/km^2 was chosen. While this apprears to be a good average for all of Europe, actual numbers for individual countries vary from 1000 persons/km^2 for Finland to 7500 persons/km^2 for Spain.
- Categories of population densities are approximate. Only two categories of urban population density (high and low) were chosen.

2.1.6 Optimisation

2.1.6.1 Overview

In addition to calculating different measure combinations on large data sets a methodology was developed to determine optimised noise control programmes for a specific line or a set of lines for a given decision policies. This methodology consists of a set of algorithms that build, evaluate and select different programmes along a decision tree, continuously rejecting all solution measure combinations that do not fit the problem constraints or that are dominated by programmes previously found. A programme is defined as a mix of global (e.g. rolling stock improvement) and local (e.g. barriers) noise control measures.

The principle behind optimisation is given in Figure 12

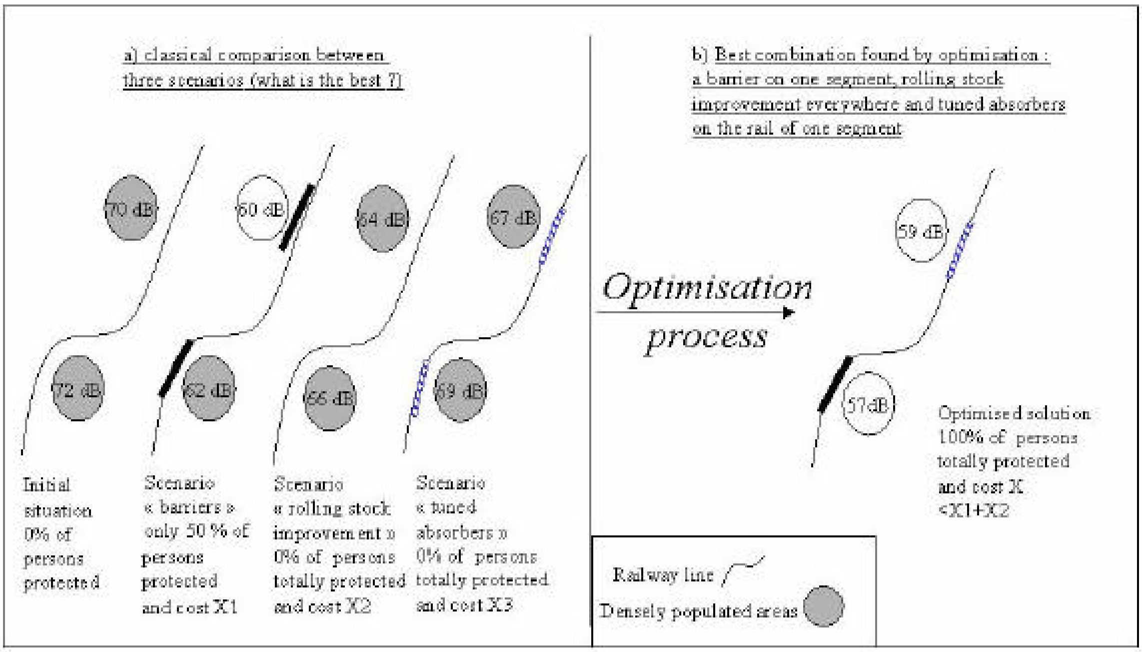


Figure 12: Optimisation Principle.

Optimisation relies on a branch and bound method. According to the studied decision policy and the problem constraints, noise control programmes are built from global and local measures following a decision tree. As soon as a partial programme is dominated by a completed one, that particular branch is not pursued any longer. Options are tested following a decision tree and as soon as a particular constraint is met, that particular branch is not pursued any longer. This is illustrated in Figure 13:

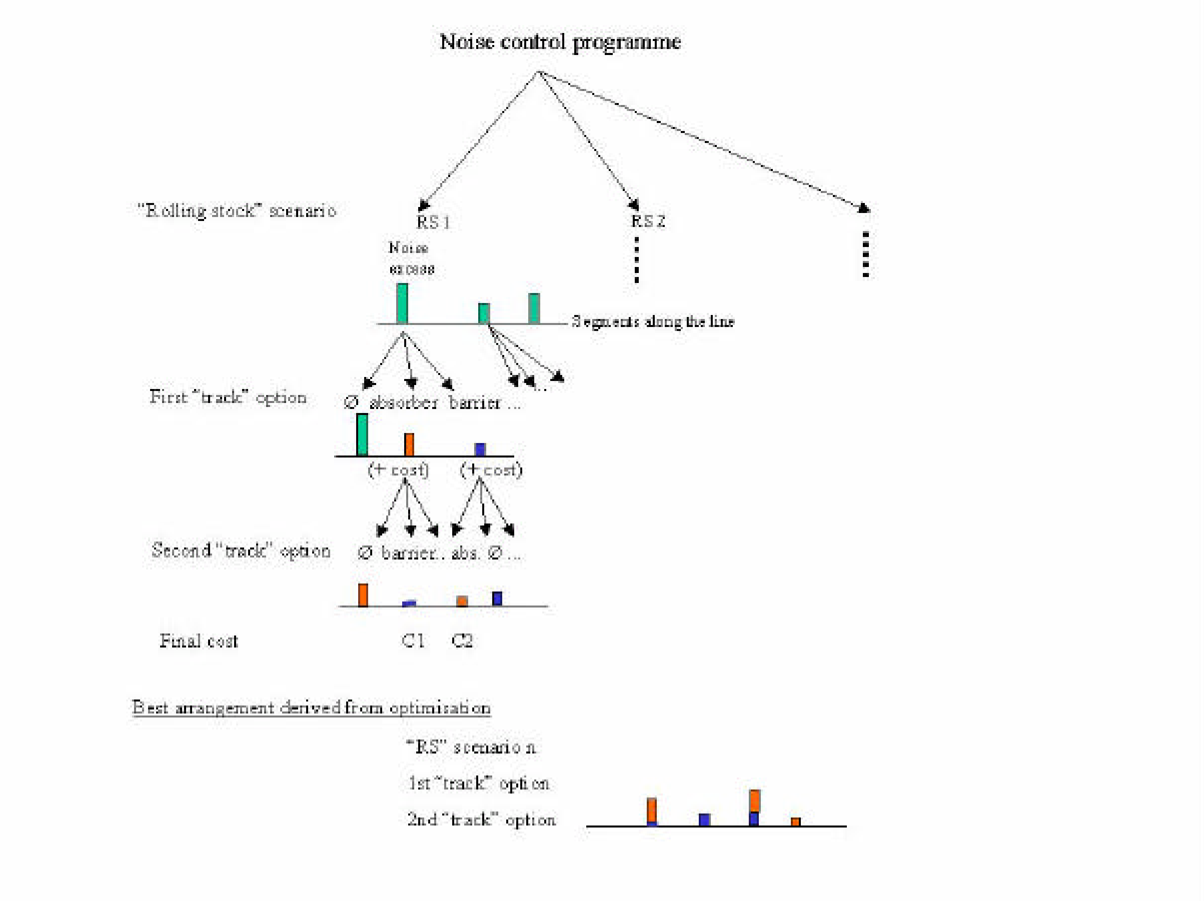


Figure 13: Illustration of the branch and bound method.

2.1.6.2 Policies

Optimisation policies can be one or a set of the following points:

- minimise the cost
- minimise the number of affected persons
- maximise the number of improved segments

2.1.6.3 Testing

The following 5 objectives were tested with the procedure

- **P1**: Determine the measure combination that for the lowest cost decreases the reception level for all segments under a certain threshold. This objective is identical to finding the minimum cost mix of acoustical solutions that protects the entire population affected by current noise creation.
- **P2:** Same as P1 but only for a given percentage of segments along the line.
- **P3:** Same as P1 but only for a given percentage of the lineside population.
- **P4:** Determine the measure combination which i) decreases the noise reception level under a given threshold for a maximum number of segments and ii) has a cost under a given budget K.
- **P5:** Determine the measure combination i) that protects the maximum percentage of the total population affected by existing railway lines and ii) whose cost is below a given budget K.

The optimisation procedure interacts with Eurano as shown in the process diagram in Figure 14.

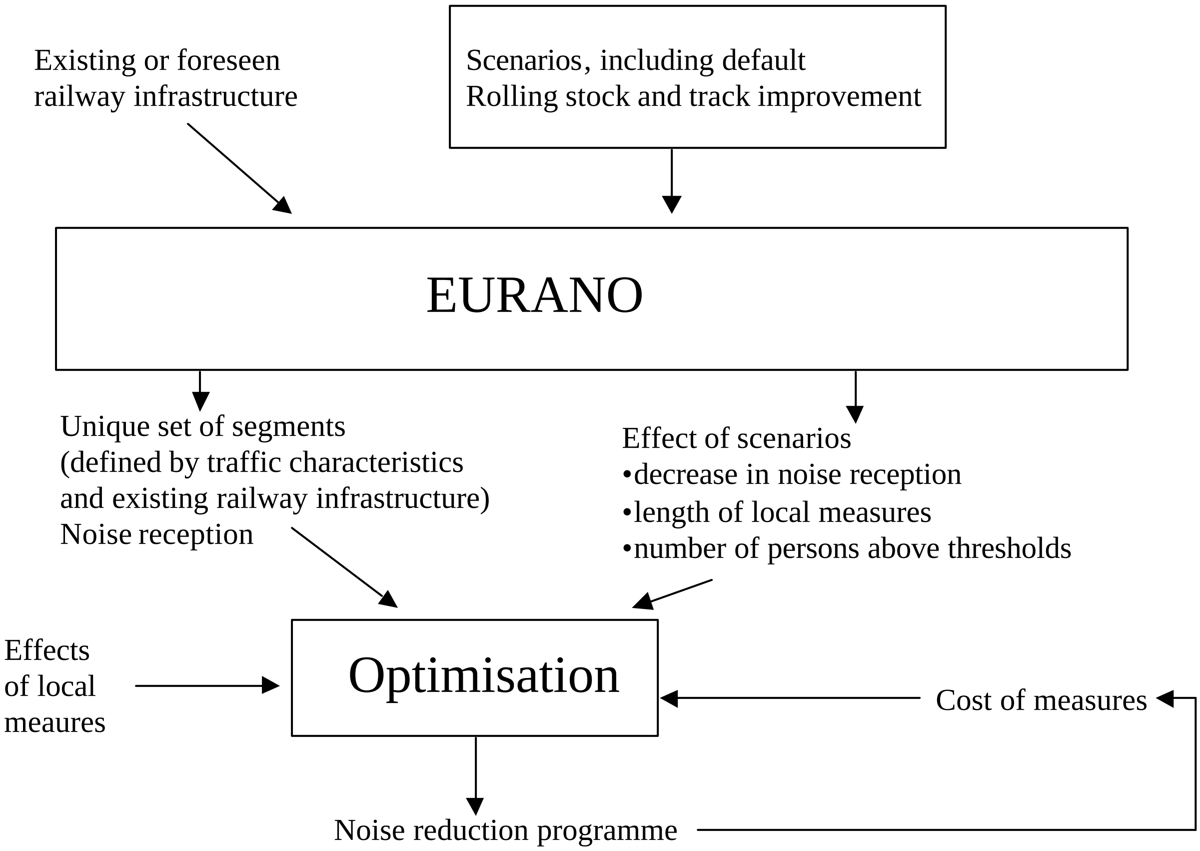


Figure 14: Process diagram showing interaction of optimisation with Eurano.

The problem is translated into a mathematical formula including decision variables, constraints and an objective function. The optimisation problem is a complex constrained non linear model. Several strategies had to be tested to get feasible running times. The decomposition in global and local sub-problems was proposed and solved with an enumerative method and heuristics. The algorithms are programmed in C++.

2.1.7 Cost Effectiveness Analysis

As part of the development of the cost effectiveness analysis tool, assessments were made for:

- The Eurano area (choice of lines for which detailed information was available)
- individual countries (21) using the extrapolation module
- a summation of the 21 countries to represent Europe

Additionally sensitivity analyses were carried out varying:

- unit costs
- implementation sequence

- number of freight wagons to be modified

Obtaining reliable statistics for population densities proved difficult and this had a significant effect on the accuracy of the result.

Figures 7, 8 and 11 show the results for the Eurano area (Figures 7 and 8) and for the 21 countries in Europe for which extrapolation data was available excluding the cost of insulated windows (Figure 11). Discussion of accuracy in section 2.1.5.7 suggests that analysis should be limited to review of the relative costs and effectiveness of the different noise mitigation measures investigated.

Figure 15 shows a general result, for the 21 European countries investigated where absolute values for the costs and benefit scales have been removed. In determining this figure costs for insulating properties with a noise level in excess of 60 dB(A) L_{den} were included.

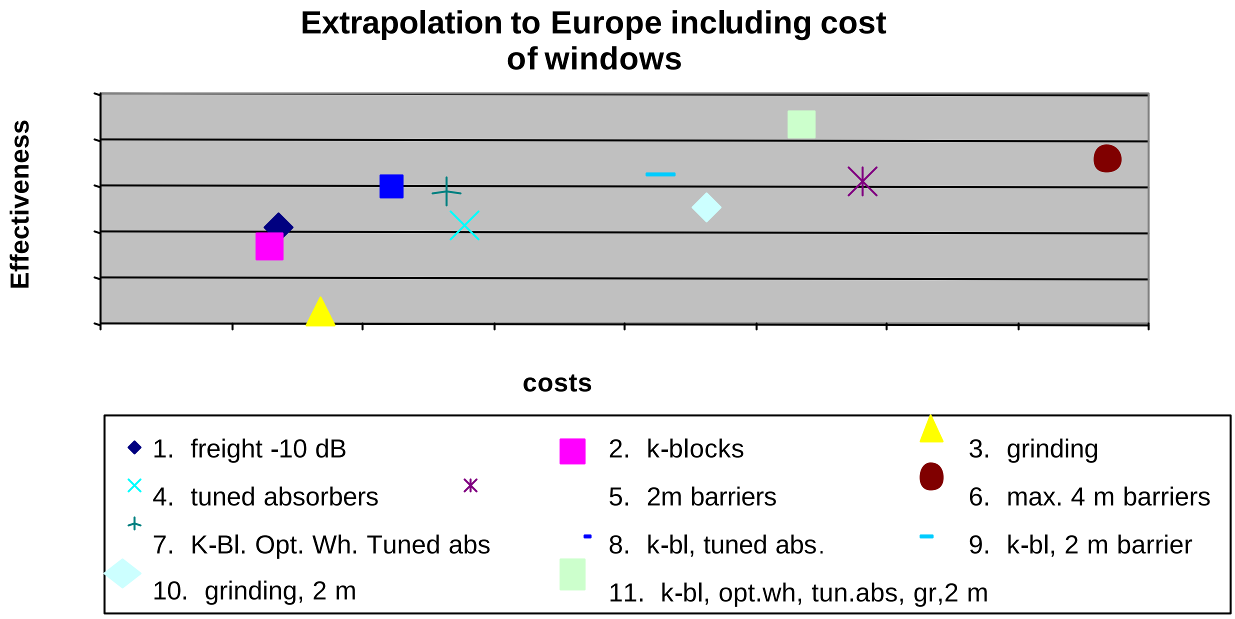


Figure 15 Cost Effectiveness Analysis

The relative positions of the different scenarios shown in Figure 15 remain reasonably consistent for all the countries investigated and for Europe as a whole.

A number of the strategic conclusions have been drawn from the cost effectiveness study.

- Smooth wheels on freight vehicles (scenarios 1 & 2) are the most efficient option. For 5% of the cost of the scenario based on noise barriers up to 4 m high, 38% of the effectiveness can be achieved. This indicates that the UIC's Action Plan to achieve smooth wheels on all freight vehicles is the correct first step to take towards quieter railways for the future.

- Noise barriers have poor efficiency especially if barriers up to 4m height (scenario 6) are considered. A higher effectiveness for 2m high barriers can be achieved at lower cost when they are combined with k-blocks (compare scenarios 9 and 5). This again supports the use of smooth wheeled freight vehicles.

A similar result could be expected for the combination of rail tuned absorbers and barriers but this combination was not tested.

- Combining rolling stock measures with track measures decreases costs whilst retaining the effectiveness. The most effective solution (scenario 11) combines k-blocks, optimised wheels, tuned rail absorbers, acoustic grinding and noise barriers limited to 2m height. For 70% of the cost of only installing barriers up to 4m height it is about 15% more effective.

- Acoustic grinding by itself was predicted to have very low efficiency. The main reason relates to wheel and rail roughness levels. Firstly, from the roughness data in the literature it is clear that wheel roughness levels exceed rail roughness levels even for disc braked wheels relative to smooth rails. The only exception is the case of high rail roughness. The benefit of even smoother rails is therefore marginal.

  Cast iron tread braked wheels certainly have a higher roughness level than smooth service rails and since the noise environment in most countries is dominated by cast iron tread braked freight at night, rail grinding will have little effect.

  If wheels with k-blocks are shown to be even smoother, TWINS calculations predict a greater benefit from acoustic grinding.

  Specific measurements in Germany indicate a much higher noise reduction from rail grinding than predicted here. A 3 dB(A) reduction is allowed in the noise prediction model for all types of vehicles irrespective of braking system. To achieve these levels, wheel roughness must be lower than reported in the literature.[3]

2.1.8 Suggestions for further study

The aim of STAIRRS work package 1 was to provide a tool to compare the cost effectiveness of different noise mitigation options at a European level. This tool was tested with the combinations described in this report and has already allowed several conclusions to be drawn. The results show, however, that analysis of additional combinations would be interesting as well as assessments based on different threshold levels. The following list contains possibilities warranting further investigation:

K-blocks, 2 m barriers and tuned rail absorbers: The results show that the combination of k- blocks and 2 m barriers as well as k-blocks and tuned rail absorbers have an excellent efficiency. The combination of all three was not tested and could provide a very interesting solution.

2 m barriers and tuned rail absorbers: Noise barrier length can be significantly reduced by adding k-blocks. A similar phenomenon can be expected, when combining 2 m barriers and tuned rail absorbers.

Acoustic grinding and k – blocks: Acoustic in combination with smooth wheels (disc-braked wheels or vehicles equipped with k-blocks) may be a very efficient measure.

[3] In Germany DB AG has developed a procedure called “Specially Monitored Track” (SMT) for the purpose of reducing noise generation at the source. The SMT process involves removing rail corrugations through a special grinding procedure and a periodic acoustic monitoring of the track section. Measurements show that the rolling noise reduction obtainable with the SMT process for non-corrugated wheels (disc-braked wheels or vehicles equipped with k-blocks) can be as much as 8 dB(A) but is considerably less pronounced in the case of trains with cast-iron block brakes. The Federal Railway Agency (EBA) in Germany approved –3dB(A) on an average over all kinds of trains. By making methodical use of the SMT process, around 5 million EURO per year can be saved on conventional noise control measures (e.g. noise barriers).

Track and vehicle dependent analysis: The effects of many measures (e.g. grinding, tuned rail absorbers) are dependent on elements of the track and on the vehicle mix. An improvement of accuracy could be achieved by making scenario noise reductions vehicle mix and track dependent.

The influence of different threshold values: The results contained in this report are based on a threshold of 60 dB(A) L_{den}. Testing the influence of different threshold values could give the basis for determining Europe wide thresholds.

Determine competitive measure costs: The tool could be used to determine unit costs of measures that must be achieved before a certain measure is competitive,

Increasing accuracy of extrapolation to individual countries: The results of the extrapolation were satisfactory in many cases. However, in countries which have a different urban density from average situations, the number of affected persons was over- or underestimated. Further studies could indicate which parameters must be used and which additional data must be collected to increase the accuracy of for each country.

Increasing accuracy of tool: Several elements of the tool could be improved:

By using a three dimensional noise calculation model, noise calculation accuracy could be improved. However, data collection is very much more expensive and calculation times would be significantly increased. An alternative could include using representative case studies. Other elements for improvement include interpolation mechanism used for analysing implementation sequences integrating the cost-benefit module into the optimisation algorithm.

2.2 Work Package 2

2.2.1 Separation Techniques

In the STAIRRS project, one of the aims of work package 2 was to develop measurement methods for railway noise that would enable characterisation of railway vehicles and tracks separately. The main purpose was to be able to apportion responsibilities between infrastructure authorities and train operators. This would also simplify the assessment of noise control measures, showing where measures should be taken, but also more clearly quantifying their effect. In the past, many noise control measures that were tested on the vehicle or on the track could often not be assessed unambiguously from a single microphone measurement. Different noise reductions were found at different sites. Disappointing experiences on in situ testing of wheel dampers, rail dampers and rail pads illustrate this issue.

Another purpose of such techniques is to be able to predict the noise emission of any vehicle on any track, if the appropriate track and vehicle data is available from measurement. It was the intention in STAIRRS to develop harmonised, robust methods that could be used for uniform data collection of track and vehicle noise characteristics; this would then provide a basis for prediction schemes and potentially for classification.

Several noise sources contribute to the overall sound level during a train passage, depending on speed:

- At low train speeds the noise from train engine, fans, brakes are predominant.
- In the speed range from approximately 40 km/h and approximately 250 km/h the rolling noise is predominant.
- For higher speeds the aerodynamic noise becomes more significant.

The measurement techniques of this project are developed for rolling noise only.

Over the past decades, understanding of wheel-rail rolling noise has improved considerably. Validated theoretical models such as TWINS have provided insight into the main influence parameters and their interaction. The TWINS model indicates that for a given wheel-track combination and particular train speed there are two excitation inputs, i.e. wheel and rail roughness, and two sound emission outputs, i.e. from wheel and from track. From this model it can also be understood that a single microphone measurement at the trackside is influenced by a large number of parameters. This is illustrated in practice by the large spread in noise levels that can occur if conditions are not well controlled.

There has always been a requirement for measurement methods that allow assessment of the noise situation under operational conditions, i.e. during a train pass-by. In the nineties, the need for separating noise emissions of the vehicle and the track was recognised and addressed in the METARAIL project. In METARAIL, a number of techniques were introduced and demonstrated. Also, first steps were taken to measure total wheel-rail roughness from railhead vibration during pass-by. It was at this point that it became clear that separation of noise radiation alone is insufficient to characterise separately the vehicle and the track. For example, a vehicle with rough wheels can cause high noise levels on a smooth and low noise track. So at the beginning of the STAIRRS project, a distinction was made between various types of measurement methods, providing different types of data. Four levels of methods were distinguished as shown in table 7.

	Obtained Quantities			
	Total	Vehicle	Track	Applications and notes
Level 0 (No separation)	L_{ptot}			Overall levels, large spread
Level 1 (Sound Separation)	L_{ptot}	L_{pveh}	L_{ptr}	For assessing track or vehicle noise control measures
Level 2 (Sound and roughness separation)	L_{ptot}	L_{rveh}, L_{Hveh} L_{pveh}	L_{rtr}, L_{Htr} L_{ptr}	For independent characterisation of tracks and vehicle
Level 3 (Sound, roughness and dynamics separation)	L_{ptot}	L_{rveh}, L_{Hveh} L_{pveh}, Mobilities and others	L_{rtr}, L_{Htr} L_{ptr} Mobilities and others	Partly using calculation, when vehicle not available

Table 7: Overview several levels of railway noise characterisation

- Level 0: This is the simplest method using a single microphone, resulting in only the overall sound level from vehicle and track which is characterised by single level or spectrum. The contributions of vehicle and track are not separated. The level 0 characterisation is used when only overall levels are required. As a consequence, the overall levels of a single vehicle type on different tracks can show a large spread due to variation in rail roughness and track parameters. Due to various track types, variation in wheel and rail roughness and train speed. Overall levels of a single track type show a large spread due to various vehicle types, variation in wheel and rail roughness and train speed.

- Level 1: The contributions of vehicle and track to the overall sound level are separated in vehicle and track contribution. Level 1 separation is used for instance when track or vehicle noise control measures are to be assessed. The contribution of a single vehicle type shows a spread due to variation in wheel and rail roughness and train speed. The contributions of a single track type show a spread due to variation in wheel and rail roughness and train speed.

- Level 2: The level 2 method also separates the vehicle and track contribution into vehicle and track transfer function and total roughness. The transfer functions give the transfer spectra from total roughness to the vehicle and track contribution to the sound level. The total roughness in turn can be separated into wheel and rail roughness. Hence the vehicle and track are characterised by four spectra: the vehicle and track transfer functions and the wheel and rail roughness. The separation in these four spectra is essential in other to predict the overall sound level for any arbitrary choice of vehicle, track and train speed, provided their transfer functions and roughness are known.

- Level 3: The vehicle and track are characterised by their acoustic and dynamic properties, which can be assessed by measurements or calculations. This method of separation is useful when the vehicle or track is not available for pass-by measurements.

Within the STAIRRS project it was agreed that the level 2 approach would be most suitable to fulfil the project objectives. It produces four fairly independent quantities, wheel roughness and vehicle transfer function, and rail roughness and track transfer function. The developed measurement techniques provide total wheel-rail roughness and the total transfer function, which can be split out into vehicle and track contributions by applying particular measurement conditions. The characteristic quantities of roughness and transfer function can be obtained from sound pressure and rail vibration time signals of a vehicle pass-by.

With the developed methods, the following applications are available:

- Assessment of wheel roughness for complete vehicles or trains from a single pass-by measurement;
- Assessment of rail roughness from multiple pass-bys;
- Measurement of a single transfer function characterising the vibro-acoustic behaviour of the track;
- Measurement of the track vibration decay rate;
- Estimation of a single transfer function characterising the vibro-acoustic behaviour of the vehicle;
- Acquisition of vehicle and track data with which predictions of arbitrary vehicle track combinations can be made.

The separation methods developed in STAIRRS are described in the following sections.

2.2.1.1 Vibro-acoustic Track Noise (VTN)

The Vibro-acoustic Track Noise method calculates the sound power from the track (rails and sleepers) using measured vibration signals (or spectra) from accelerometers at the rail and sleeper as inputs to simple noise radiation models. These models consider the radiating surface area and radiation efficiency of sources and a directivity pattern for sound propagation taking account of absorption and reflections near the sources.

Vehicle noise is determined by subtracting the predicted track noise from the measured total noise using the following equations:

$$L_{p,veh} = 10\log_{10}(10^{(L_{p,tot}/10)} - 10^{(L_{p,track}/10)})$$

where:

$L_{p,veh}$ = sound pressure level of vehicle contribution [dB re 20 μPa]

$L_{p,tot}$ = measured total sound pressure level [dB re 20 μPa]

$L_{p,track}$ = calculated sound pressure level of track contribution [dB re 20 μPa]

For frequency bands where $L_{p,track}$ is predicted to be higher than measured $L_{p,tot}$, $L_{p,track}$ is given the value ($L_{p,tot}$ - 0.3) dB, and the vehicle level is then set to ($L_{p,tot}$ – 12) dB.

Track Radiation Theory

$L_{p,track}$ is calculated from the following theory.

Both the rail and the sleeper are considered to vibrate homogeneously on their surface in contact with the air. This means that no phase shift is assumed between different points on these sources. This assumption, that corresponds to a pulsating infinite cylinder model, introduces a small error that will be considered later. All the power levels are then attributed to line sources: one for the rail vertical vibration, one for the rail lateral vibration, and one for the sleeper vertical vibration. The rail in the vertical direction and the sleeper are modelled as line monopoles, the rail in the lateral direction is modelled as a line dipole.

Basically, the source model considers separately the noise emission of one rail and half of the sleeper from that of the other rail and other half of the sleeper. Then the two are added.

A specific energy contribution (energy per metre) is associated with each line source. This specific energy must be equal to the sound energy produced by a uniform vibrating surface.

$E = W_{\mathrm{source}} \cdot \Delta t = s \cdot A \cdot v^2_{\mathrm{rms}} \cdot r \cdot c \cdot \Delta t$

E = energy per metre [J/m]

W = radiated sound power per metre of track [W/m]

s = sound radiation efficiency of the source[-]

Δt = averaging time [s]

A = area of the external vibrating surface per metre [m]

v_{rms} = r.m.s. of velocity of vibration [m/s]

r = air density [kg/m^3]

c = sound speed [m/s]

If the averaging time Δt is long enough to consider the sound contribution of all vehicle pass-by, the effect of rail vibration decay far from the contact point is automatically evaluated. Once the surface velocity and area are known, the radiated sound power can easily be obtained if the radiation efficiency is known. In the case of the sleeper, this is taken from a baffled plate model as

$$s = \frac{1}{1+\left(\frac{f_{cs}}{f}\right)^2}$$

$$f_{cs} = \frac{c}{\sqrt{2pwl}}$$

σ = radiation efficiency

f = frequency

f_{cs} = critical frequency

w = sleeper width

l = sleeper length

In the case of the vertical rail radiation, σ is computed assuming an oscillating infinite beam model. The radiation efficiency can be retrieved once the height and width are known, and it does not change significantly between typical rail shapes like UIC60 and UIC54.

The dipole correction introduced for the lateral rail vibration is based on the height of the microphone over the track level, so that the angle from the track level can be calculated and, from that, the dipole factor:

$Q_{\vartheta} = 2 \cos^2 (\mathrm{atan}\,(h/d))$.

h = microphone height

d = microphone distance

Since all computations are made for a reference track length of 1 metre, source energy is a known quantity (with respect to 1 metre) and sound pressure can be easily calculated at a certain distance, applying a line source model. The sound pressure for the monopole line source is then found as:

$p^2_{\mathrm{rms}} = W \cdot r \cdot c / 2\pi d,$

while for the dipole line source it is

$p^2_{\mathrm{rms}} = (W \cdot r \cdot c / 2\pi d) \cdot Q_{\vartheta}.$

Finally, the contributions of the near rail and half-sleeper and far rail and half-sleeper are added logarithmically to give the total track sound pressure.

A model for the sound power flow is developed to estimate the sound transfer function from the rails and sleepers to the microphone. As the shape of the vehicle floor and the space between ballast and vehicle is different for different types of vehicles, the model attempts to give only a course description of the energy flow. The rails are modelled by 4 line sources at half the rail height, while the sleepers are modelled by 2 line sources at ballast level.

It is considered that the contribution from the near rail to the microphone will mainly consist of direct sound energy, as reflective energy from that rail will be radiated to the opposite side of the track. For this rail the indirect sound is therefore disregarded while the direct sound is written as

$W_{\mathrm{direct}} = W_{\mathrm{source}} \cdot (\zeta/2\pi)$

where:

W_{direct} = direct propagating sound power [W/m];

W_{source} = sound power per meter of line monopole source [W/m];

ζ = angle for direct sound radiation.

The reflected sound power for the farther rail is a mixture of several reflections at the ballast and vehicle body. Given the geometry of the sources and track and vehicle floor, most reflected sound rays that reach the microphone will encounter two reflective surfaces, the ballast and the car body floor. The composite absorption factor after these two reflections is given by:

$\alpha = \alpha_{\mathrm{ballast}} + \alpha_{\mathrm{vehicle}} - \alpha_{\mathrm{ballast}} \cdot \alpha_{\mathrm{vehicle}}$

α = composed absorption factor [-];

$\alpha_{\mathrm{ballast}}$ = ballast absorption factor [-];

$\alpha_{\mathrm{vehicle}}$ = vehicle body absorption factor [-].

For the two line dipoles (lateral vibrating rail) the factor Q_{ϑ} also has to be incorporated. It is noted that the directivity and reflection model described here is not an essential part of the VTN model. It can be replaced by a measured (average) transfer function from the rails to the microphone, if available.

Once the several equivalent sound power sources are determined, sound pressure can be easily computed.

Validation

In the validation campaign it was assessed that VTN calculates the track contribution within +/- 2 dB(A). The accuracy of the vehicle contribution varies with the difference between track and total noise. For dominant vehicles, i.e. low track contributions, the vehicle noise is calculated with a high accuracy. If the track is dominant, the vehicle contribution is calculated with much less accuracy, but in that situation the vehicle will generally not be an issue.

2.2.1.2 Multiple Input Single Output (MISO)

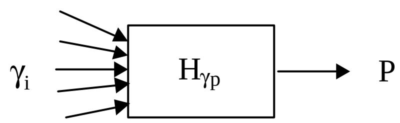
The basic idea was to develop a real time separation method based on the signal processing of pass-by measurement data.

The process first determines the track contribution and then subtracts it from the total noise to obtain the vehicle contribution.

The MISO separation method relies on 4 basic steps:

Step 1: Characterisation of the vibroacoustic track Frequency Response Function (FRF) between the track vibration and the acoustic pressure measured with the near field microphone. It is assessed using only the records taken from parts of signals which are free of vehicle contribution (i.e. : midway between bogies)

The track FRF is defined as : $\{H_{\gamma p}(f)\} = [G_{\gamma\gamma}(f)]^{-1} \cdot \{G_{\gamma p}(f)\}$



where γ_i (t) $_{i=1,n}$ - is the acceleration measured on the n transducers attached to the track,

p(t) is the near field acoustic pressure (t representing the time)

$\{H_{\gamma p}(f)\}$is the input/output vector of the track vibroacoustic FRF,

$[G_{\gamma\gamma}(f)]$ represents the input cross Power Spectral Density matrix between all vibration signals at frequency f,

$\{G_{\gamma p}(f)\}$corresponds to the output cross Power Spectral Density vector at frequency f.

$G_{xy}(f) = G_{xy} = \frac{2}{T} \cdot E[X^* \cdot Y^t]$ with

E[] : expected value

X(f), Y(f) : Fourier transforms of x(t) and y(t)

T : record length ($T \rightarrow \infty$)

* : complex conjugate

^{t} : transpose

Step 2 : Computation of the near field track acoustic contribution during a whole vehicle pass-by. This contribution is calculated as the track FRF (result of the step 1) multiplied by the measured track accelerations integrated over the whole vehicle pass-by.

$$G_{pp}^{track}\Big|_{pass-by} = \{H_{\gamma p}\}^H \cdot [G_{\gamma\gamma}] \cdot \{H_{\gamma p}\}$$

The quadratic acoustic pressure due to the track in the frequency band (f, Δf) is then obtained by :

$$P^2_{track}(f,\Delta f) = \int_{\Delta f} G^{track}_{pp}(f)\Big|_{pass-by} \cdot df$$

Step 3 : Calculation of the near field vehicle contribution as the difference between the total noise and the track noise

$$P^2_{véhicle}(f,\Delta f) = P^2_{total}(f,\Delta f) - P^2_{track}(f,\Delta f)$$

Step 4: Transposition of results to the "target" microphone located at the standardised position (either at 25m or 7.5m from the centre of the track), assuming the same vehicle to track contribution ratio remains.

$$\left.\frac{P^2_{total}(f,\Delta f)}{P^2_{track}(f,\Delta f)}\right|_{near\ field} = \left.\frac{P^2_{total}(f,\Delta f)}{P^2_{track}(f,\Delta f)}\right|_{s\tan dard\ position}$$

$$Lp_i(f,\Delta f) = 10 \cdot \log_{10}\left(\frac{P_i^2(f,\Delta f)}{P_0^2}\right) \quad \begin{array}{l} i = total, vehicle, track \\ P_0 = 2 \cdot 1\theta^{-5}\,Pa \end{array}$$

Derivation of the Track Transfer Funtion :

The MISO separation process is essentially based on a reliable assessment of the track FRF (performed in the step 1). The number and the position of each accelerometer on the track as well as the distance and the height of the "near field" microphone are key parameters.

This FRF calculation is mainly based on two main points :

1. Use of particular characteristics of the near field acoustic signal measured during a train pass-by; when the microphone is opposite the bogie area, both the vehicle and track acoustic contributions are important and add up to produce the total noise, while only the track radiates noise when the microphone is opposite the midpoint between bogies.
   This assumption has been experimentally checked and validated during a field test where both track and vehicles dynamic behaviours were monitored.
2. An automatic selection, at each frequency, of the transducers which are the most representative of the track dynamics; it has been proved that although a single transducer is not sufficient to accurately characterise the track dynamics, too many transducers also corrupt the track FRF assessment because of the redundant information introduced by the correlations existing between accelerometers. This selection is carried out with a Principal Component Analysis (PCA) procedure.

   The track FRF is then straightforwardly computed using the formula $\{H_{gp}(f)\} = [G_{gg}(f)]^{-1} \cdot \{G_{gp}(f)\}$ as all the singularities of the input matrix [$G_{\gamma\gamma}$] (which make it non invertible) are directly handled by the Singular Value Decomposition technique included in the PCA procedure.

2.2.1.3 Pass-by Analysis (PBA)

Indirect Roughness Measurements

The roughness of wheel and rail can be measured with commercially available measurement devices. However, there are some disadvantages to this 'direct' measurement method:

- The method is very time consuming and required access to the rails.

- The directly measured roughness varies significantly if the lateral position of the probe on wheel tread or rail head is altered. If the actual lateral position of the wheel-rail contact is not known, the relevant roughness is also not known. By the indirect roughness measurement, the effective roughness at the actual lateral contact position on both track and wheel during the train pass-by is determined.
- The instrument senses the roughness of wheel and rail with a probe of small radius. This roughness differs from the roughness, which is sensed by the contact area, as explained earlier.

To overcome these disadvantages, the indirectly measured roughness is proposed.

The indirect roughness method uses the raw time data of a vertical vibration measurement by an accelerometer underneath the rail, see figure 16.

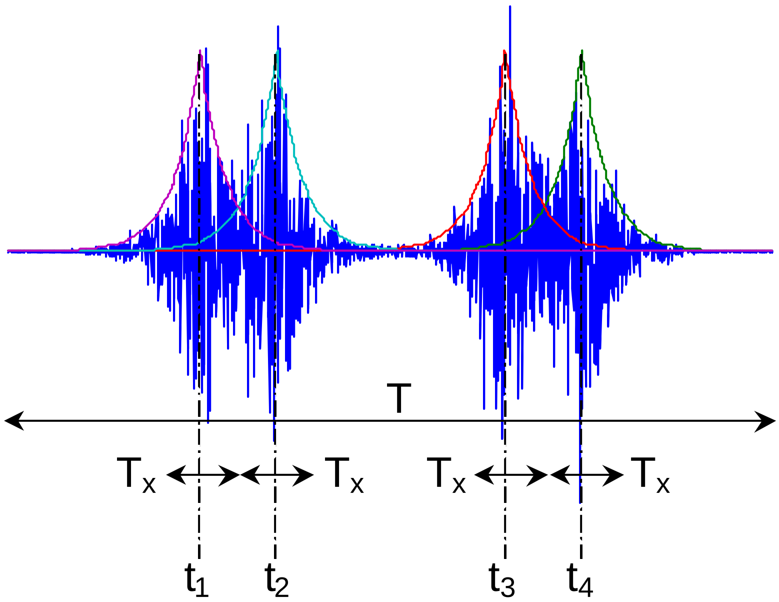


Figure 16: Vertical acceleration measurement during four wheel passages.

The combined effective roughness of wheel and the rail is determined indirectly from the ? octave band levels $L_{a,meas}(f_{to})$ of the average acceleration over the wheel passage interval T_x . From this spectrum the acceleration spectrum at the rail head $L_{a,head}(f_{to})$ is calculated, followed by the acceleration at the contact point $L_{a,contact}(f_{to})$. The acceleration is converted to the displacement $L_{x,contact}(f_{to})$ at the contact point. The last step is the conversion from the displacement to the combined effective roughness. These steps are described by the following equation:

$$L_{r,tot}(f_{to}) = L_{a,meas}(f_{to}) - A_1(f_{to}) - A_2(f_{to}) - A_4(f_{to}) - 40\log_{10}(2pf_{to})$$

where

$L_{r,tot}(V/f_{to})$	? octave band levels of combined effective roughness of wheel and rail
$L_{a,meas}(f_{to})$	? octave band levels of measured ***equivalent*** vertical rail acceleration, averaged over wheel passage interval T_x.
$A_1(f_{to})$	the level difference between the average vibration at the measurement position (for example underneath the rail) and the rail head.

$$A_1(f_{to}) = L_{a,meas}(f_{to}) - L_{a,head}(f_{to})$$

$A_2(f_{to})$ the level difference between the vibration displacement at the contact point on the rail head and the combined effective roughness $L_{r,tot}(V/f_{to})$:

$$A_2(f_{to}) = L_{x,contact}(f_{to}) - L_{r,tot}(f_{to})$$

($A_3(f_{to})$ omitted in this report, but numbering of conversion spectra maintained for comparison with literature)

$A_4(f_{to})$ the level difference between the vibration at the contact point and the average vibration over the wheel passage interval:

$$A_4(f_{to}) = L_{a,head}(f_{to}) - L_{a,contact}(f_{to})$$

$40\log_{10}(2\pi f_{to})$ conversion from acceleration $L_{a,contact}(f_{to})$ to displacement $L_{x,contact}(f_{to})$

f_{to} ? octave band centre frequencies

V train speed (m/s)

The three conversion spectra will be discussed in detail in the following sections

Conversion spectrum A_1

Positioning the accelerometer on the railhead is not possible for practical reasons. The accelerometer will be located on a different part of the rail cross section. The conversion spectrum $A_1(f_{to})$ from the measured acceleration $L_{a,meas}(f_{to})$ to the vertical acceleration of the rail head $L_{a,head}(f_{to})$, accounting for the cross-sectional deformation of the rail, depends on the location of the accelerometer on the rail cross section. In literature it has been shown, that an accelerometer underneath the centre of the rail foot, and in vertical direction, gives a good representation of the vertical vibrations of the railhead. For this situation the spectrum $A_1(f_{to})$ = 0 up to 4 kHz.

Conversion spectrum A_2

The level difference $A_2(f_{to})$ between the vibration displacement at the contact point $L_{x,contact}(f_{to})$ on the rail head and the combined effective roughness $L_{r,eff}(V/f_{to})$, which describes to which extent roughness induces rail vibration, is the result of the wheel rail interaction and is given by:

$$A_2 = 20\log_{10}\left(\frac{|a_R|}{|a_R + a_W + a_C|}\right)$$

where

a_R rail receptance,

a_W wheel receptance and

a_C receptance of the contact stiffness

An example of the receptances is given in figure 17

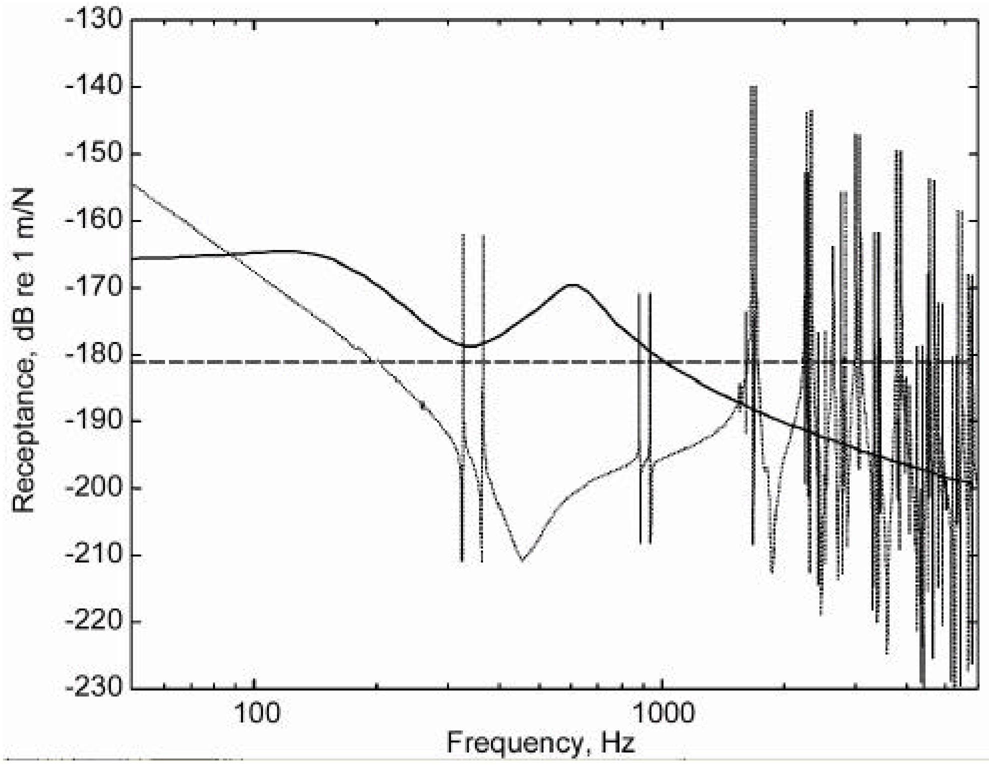


Figure 17: Vertical receptances for reference situation: — rail, - - - contact stiffness and ····· wheel.

Frequencies where $|\alpha_R| » |\alpha_W+\alpha_C|$ give $A_2 \approx 0$ dB. As shown in the example of figure 18, this often occurs in practice between 100 and 1000 Hz.

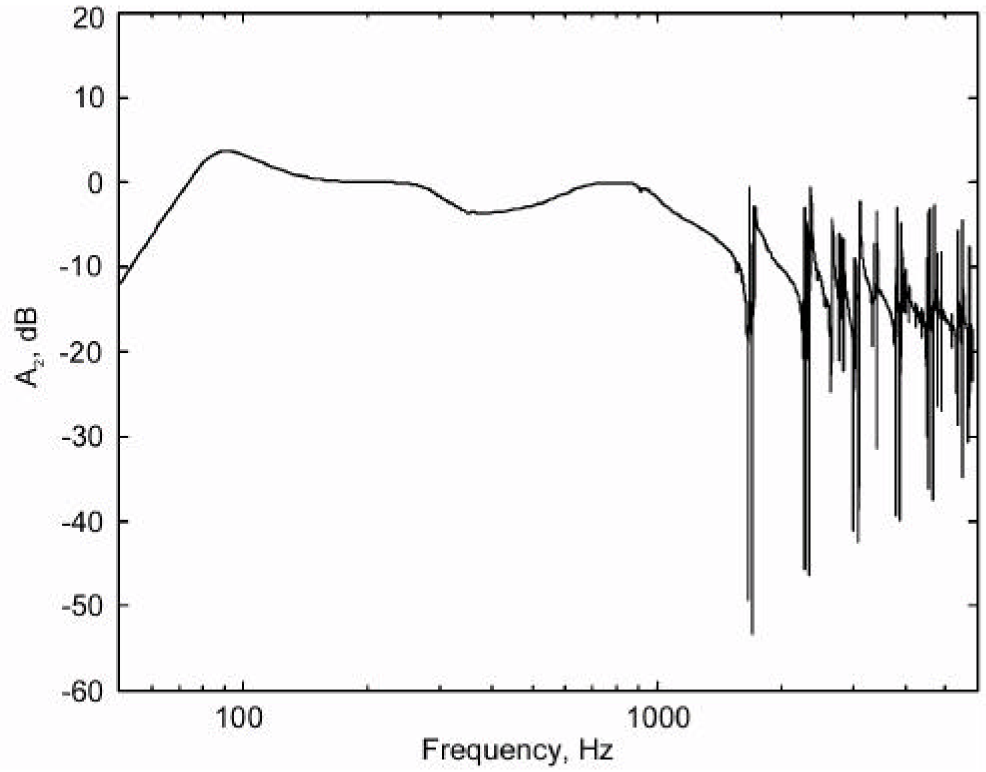


Figure 18: Narrow band conversion spectrum of $A_2(f)$ for reference situation.

A_2 has been determined for a range of parameter values using the TWINS software. The reference situation consisted of a standard UIC 920 mm diameter freight wheel, a track with UIC60 rails, bibloc sleepers at 0.6 m spacing and rail pads of (loaded) stiffness 400 MN/m. The (loaded) ballast stiffness is set to 100 MN/m per sleeper end. The influences of pad stiffness, ballast stiffness, sleeper type, contact position on rail and wheel, wheel load and wheel type on the spectrum A_2 were evaluated. The pad stiffness is shown to be the most influential parameter. In the frequency range from 100 to 3150 Hz inclusive, the spectrum A_2 can be determined to an accuracy of ±3 dB for application to conventional wheels, provided that the rail pad stiffness can be allocated to one of the three categories, as listed in table 10. This makes the accuracy of the indirect roughness estimation not smaller than the direct method with a probe of small radius. To increase the accuracy of the prediction of the combined effective roughness, several measurements with different train speeds have to be averaged. In that case, the peaks and dips in frequency spectrum A_2 spread out over a wider wavelength range.

Frequency (Hz)	Soft pad	Medium pad	Stiff pad
63	1.0	−3.0	−3.0
80	4.1	2.3	2.3
100	2.7	2.6	2.6
125	0.9	0.8	0.8
160	0.1	0.0	0.0
200	0.0	0.0	0.0
250	−0.6	0.0	0.2
315	−1.2	−2.6	−0.1
400	−1.3	−3.9	−2.8
500	−0.9	−4.8	−6.5
630	−0.9	−3.2	−8.1
800	−1.6	−2.6	−6.9
1000	−2.7	−4.3	−5.0
1250	−5.6	−6.2	−4.4
1600	−8.0	−7.5	−6.4
2000	−9.5	−8.8	−8.4
2500	−10.0	−9.8	−9.5
3150	−11.3	−11.2	−11.1
4000	−13.7	−13.6	−13.6
5000	−14.9	−14.8	−14.8

Table 8: Spectra $A_2(f_{to})$ for three categories of rail pad stiffness

	Soft pad	Medium pad	Stiff pad
bibloc sleeper	≤ 400 MN/m	400 - 800 MN/m	≥ 800 MN/m
monobloc sleepers	≤ 800 MN/m	≥ 800 MN/m	–
wooden sleepers	all	–	–

Table 9: Proposed ranges of pad stiffness applying to different categories of pads used in defining standard spectra for A_2

The definition of soft, medium or stiff pad depends on the sleeper type. Different pad stiffness ranges apply to bibloc and monobloc sleepers, as shown in table 9.

The roughness wavelength range is determined by the frequency range (100 to 3150 Hz for accurate results of the indirect roughness method) and the train speed, see figure 19.

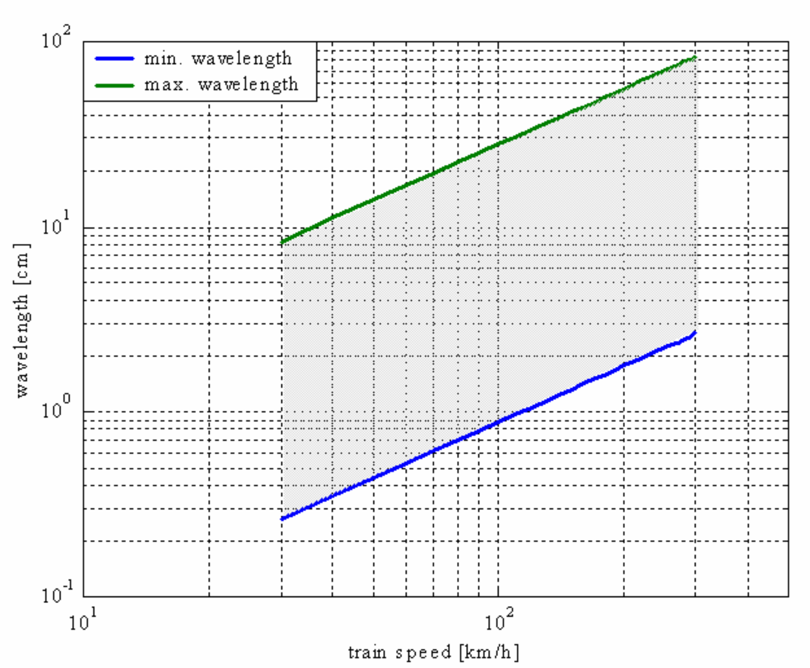


Figure 19: Maximum wavelength range that can be covered by the indirect roughness method as a function of the pass-by speed.

Conversion spectrum A_4

The level $A_4(f_{to})$ difference between the vibration at the contact point $L_{a,contact}(f_{to})$ and the average vibration over the wheel passage interval $L_{a,head}(f_{to})$ depends on the spatial vibration decay D of the track:

$$A_4\left(f_{to}\right)=L_{a,head}\left(f_{to}\right)-L_{a,contact}\left(f_{to}\right)=10\log_{10}\left\{\frac{8.686}{V\,DT_x}\left\{1-e^{\left(-\frac{VDT_x}{8.686}\right)}\right\}\right\}$$

The time interval T_x is explained in figure 14. The vibration decay D can be derived from hammer impact measurement (usually an unloaded track) or from the pass-by measurement (loaded track).

Transfer Function from Effective Roughness to Passby Noise

The combined transfer function ($L_{H,tot}$) is found by subtracting the total effective roughness ($L_{r,tot}$) from the total sound level $L_{p,tot}$)

$$L_{H,tot}=L_{p,tot}-10\log_{10}\left(\frac{N}{L}\right)-L_{r,tot}$$

Measurement requirements have been identified to provide the necessary data.

This separation only results in combined roughness and combined transfer function. For further separation other information is required.

For instance, direct measurement of either wheel or rail roughness will allow the other to be calculated from the total effective roughness and the filtering at the contact. Additional techniques can be used for determining the transfer function for wheels and rails using reciprocity techniques and TWINS simulations.

The more interesting options relate to direct measurement using either reference vehicles or reference tracks.

The reference vehicle assessment requires the vehicle to be 6 dB quieter than the track in all 1/3 octave bands. It can then be assumed that the total noise is equal to the track noise and the track transfer function has been measured. The following vehicle types have a transfer function that is lower than the transfer function of a wagon with a standard undamped 920 mm freight wheel and are potential candidates for reference vehicles:

- Small diameter wheels with a thick web have fewer wheel modes in the relevant frequency range up to 5 kHz. Their transfer function can therefore be significantly lower compared to the reference wheel.
- Wheels with dampers have a lower transfer function compared to the standard wheels. The requirement of a wheel transfer function which is at least 6 dB lower than the track is usually not met for a 920 mm wheel with wheel damper over the complete frequency range from 100 to 3150 Hz.

Conversely the reference track has to be 6 dB quieter in all 1/3 octaves than the wheel. In this case all the noise is assumed to be radiated by the wheel and the wheel transfer function is obtained.

Low transfer function tracks will have high spatial decay and low radiation efficiency. This is likely to be achieved by using tuned absorbers on the rails.

It must be stated however that, to date, no reliable designs for reference wheels and reference tracks have been identified.

PBA Software

The indirect roughness technique and the transfer function measurement technique have been implemented in a single software tool called ‘Pass-by Analysis Software. This program has railhead vertical vibration, sound pressure signals, train speed and wheel positions as inputs. It can derive the total transfer function and combined effective roughness. Depending on the measured configuration, estimates can be obtained for track or vehicle roughness and transfer functions. The PBA also can also derive track spatial decay from the rail vibration signal, which is used as an intermediate parameter.

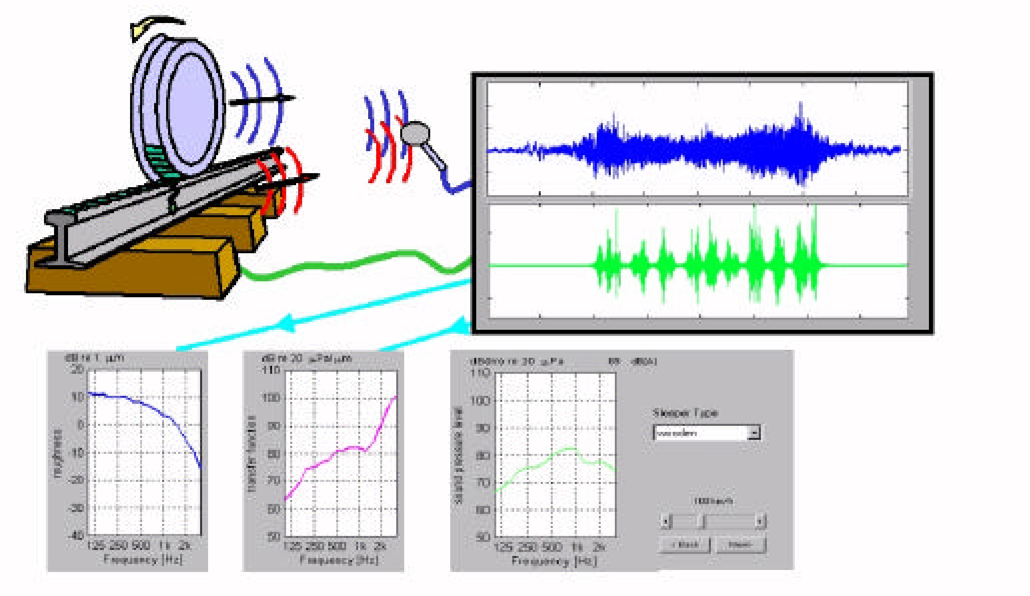


Figure 20: PBA Software

2.2.1.4 Level 2 Separation using VTN/MISO and PBA

In addition to the level 2 separation possibilities described in section 2.2.1.3, that capability can be provided by combining the VTN or MISO and indirect roughness techniques.

The contributions to total noise from vehicle ($L_{p,veh}$) and track ($L_{p,track}$) are derived using the VTN or MISO technique. PBA provides an indirect measurement of total roughness ($L_{r,tot}$). The vehicle and track transfer functions ($H_{vehicle}$ and H_{track} respectively) are derived from the following equations:

$$H_{vehicle} = L_{p,veh} - L_{r,tot} + APL_{vehicle}$$

$$H_{track} = L_{p,track} - L_{r,tot} + APL_{vehicle}$$

Where $APL_{vehicle}$ is the axle per metre correction for the vehicle.

An additional direct measurement of either wheel or rail roughness will allow the remaining roughness, for level 2 separation, to be calculated from the indirect total roughness.

This technique has been used to separate data obtained in the measurement campaign.

2.2.1.5 Theoretical Models at level 3 of the WP2 Database

‘Level 3’ of the database describes the vibro-acoustics of the vehicle and track in terms of a mechanical/acoustical model. This allows more analytical studies of the generation of noise and the ability to predict noise contributions from the vehicle and the track taking into account their designs. Within the context of the tools that the STAIRRS project delivers these models will be needed to predict transfer functions to fill in incomplete information at level 2 of the database, *e.g.* where predictions are to be made for new vehicle or track components/designs before they are available for running measurements, or simply where the measurement information is incomplete. They also provide the capability to take into account cases which do not fit into the assumptions associated with the calculation of total noise used in level 2, *i.e.* where the track transfer function is not independent of the vehicle or *vice versa*.

Using the TWINS model, it is possible to evaluate rolling noise as a function of the wheel and track design from the roughness of the wheel and rail. The TWINS model contains several different models for the track. It also allows the introduction of measured data at different stages of the modelling process, where appropriate, so that more robust 'hybrid' measurement/calculation results can be produced.

TWINS has been used extensively to study the noise generation of different wheels and tracks and to derive designs that reduce sound emissions. In these studies, the models were used to predict the *change* in sound *power* radiated by the wheel or track due to a limited number of design changes. Some simplifications are used in the models to carry out the past studies. For example, for wheel design variations it is sufficient to use the simplest track model - a Timoshenko beam on a continuous, two-layered, elastic foundation. Alternatively, where the effects of different aspects of the track design are required, the most appropriate track model can be chosen.

The use of TWINS to provide and analyse the level 3 data of STAIRRS, is different from its previous use. Now, the models are required to predict, as closely as possible, the *absolute* sound *pressure* level. It was identified in the STAIRRS proposal that this would require a new, more detailed, model of the track vibration response to be produced. An increased scope of the model is also required. It has been shown in recent research that effects of arbitrary sleeper spacing, non-linear pad stiffness and the reflections of vibration in the rail by multiple wheel contacts can all be significant in the generated level of noise from the track. This enhanced track model is called *cobra* (**Co**mposite **b**eam **ra**il).

New track model

The *cobra* model is based on composite beam models for the vertical and lateral direction for an infinite rail supported at a finite, but large number of sleepers. Figure 21 shows the model which has 'nodes' at each of the points of contact between the rail and the supports and also between the rail and the wheels. There are two types of wheel contact node, the contact at which the external force generated by the roughness input is applied, and the contacts with other wheels which are regarded as passive. The role of these is to cause partial reflections of the vibration along the rail. No external force is applied at these points in the model. Assuming harmonic solutions, the complex amplitudes of displacement at each node are $\mathbf{u}^T = [u_x, u_y, f_z]$, *i.e.* having three degrees of freedom in the vertical, lateral and cross-sectional rotation directions.

A frequency-domain matrix equation is set up using dynamic stiffness matrices to represent the infinite rail beam and each of the structures attached to it.

For the rail, a dynamic flexibility matrix, a , is first constructed by calculating the transfer receptance between the degrees of freedom at each node and every other degree of freedom of the rail. These are calculated efficiently using analytical solutions for separate composite-beam models for the vertical and lateral dynamics of the rail. The flexibility matrix is then inverted to give the element dynamic stiffness matrix for the rail, $\mathbf{K}_R$ of order $3N$ where N is the number nodes. The vertical and lateral dynamics are coupled by specifying an offset of the contact position laterally away from the rail's vertical axis of symmetry, and by applying the lateral contact force at the top of the rail.

A simplified mass and spring model is used for the passive wheel elements. This ignores the modal behaviour of the wheel above about 1.5 kHz for the purpose of the track model. The full modal model is still used for the contact receptance and vibration response of the wheel itself in other parts of TWINS. For the rail support elements, a subsystem model is used that incorporates the effects of a bending sleeper and a frequency dependent ballast stiffness. As with all other components of the model, the damping in the rail pad and ballast is introduced as a loss factor.

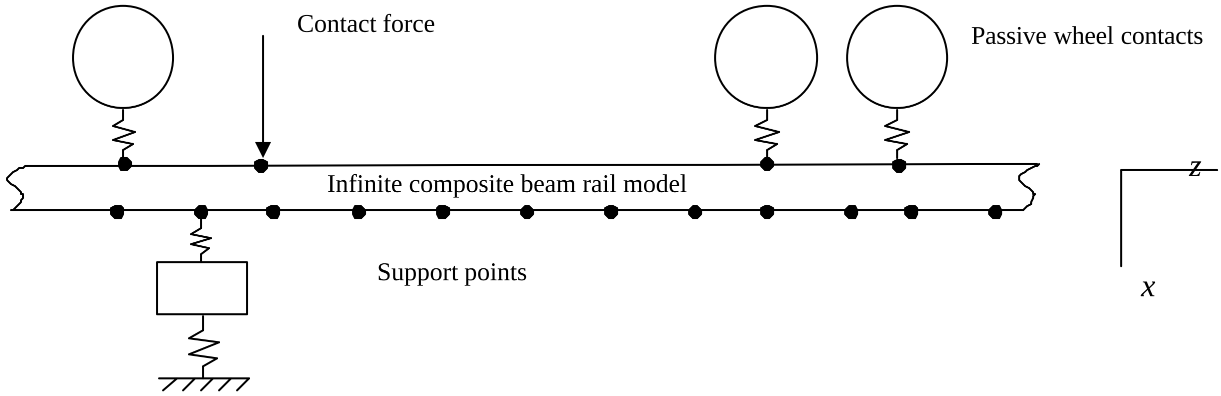


Figure 21. Diagram of the new track model, '*cobra*'.

A 'global' dynamic stiffness matrix, **K**, is the result of addition of each of the 'element' matrices having regard for the degrees of freedom of the whole system.

K is solved for the displacement amplitudes **U** due to an externally applied unit force (first vertical then lateral), contained in the vector $\mathbf{f}_e$, using $\mathbf{K}\,\mathbf{U} = \mathbf{f}_e$. The direct receptance at the loading wheel contact is available in **U**. Once the nodal displacements are known, the response of the sleepers can be calculated using the sleeper-element model. The internal reaction forces $\mathbf{f}_i$ on the rail are calculated as $\mathbf{f}_i = \mathbf{K}_R\,\mathbf{U}$ and this allows the response at large number, M, of points along the rail to be calculated using a $3M$ by $3N$ version of the rail receptance matrix that is quick to calculate.

The software allows the whole calculation to be carried out for a number of contact positions within a sleeper span so that the vibration response and resulting noise radiation can be averaged to represent that of a moving train.

The model allows arbitrary positioning for the sleeper supports and, by varying the parameters of the supports as a function of their preload under the wheels, is able to account for non-linearity in the ballast and the rail pad.

To illustrate the differences in the results of the new model from existing TWINS track models, the vertical point receptances for a UIC 60 rail section resting on rail pads of dynamic stiffness 350 MNm^{-1} and bibloc sleepers every 0.6 m are compared in Figure 22. All results show the ballast resonance at about 90 Hz and the rail pad resonance at about 530 Hz. Above this frequency differences are noted as each model accounts differently for rail modes (eg "foot flapping", "pinned-pinned" resonances) and the propagation of waves along the rail. When the effects of the other wheels of a single carriage resting on the track with one of the inboard wheels as the active wheel are included it can be seen to change the point receptance significantly for frequencies above the pad resonance where waves propagate freely in the rail.

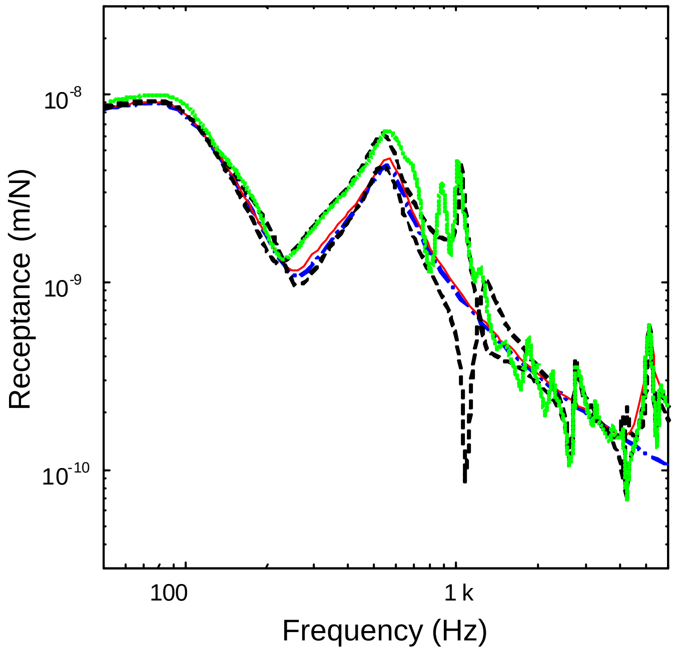


Figure 22. Direct vertical receptance at the contact
(- · - · Timoshenko beam model; ——— periodic structure model; - - - - new model with contact over sleeper and midway between sleepers; ······ new model with one carriage of passive wheels, contact at mid-span position).

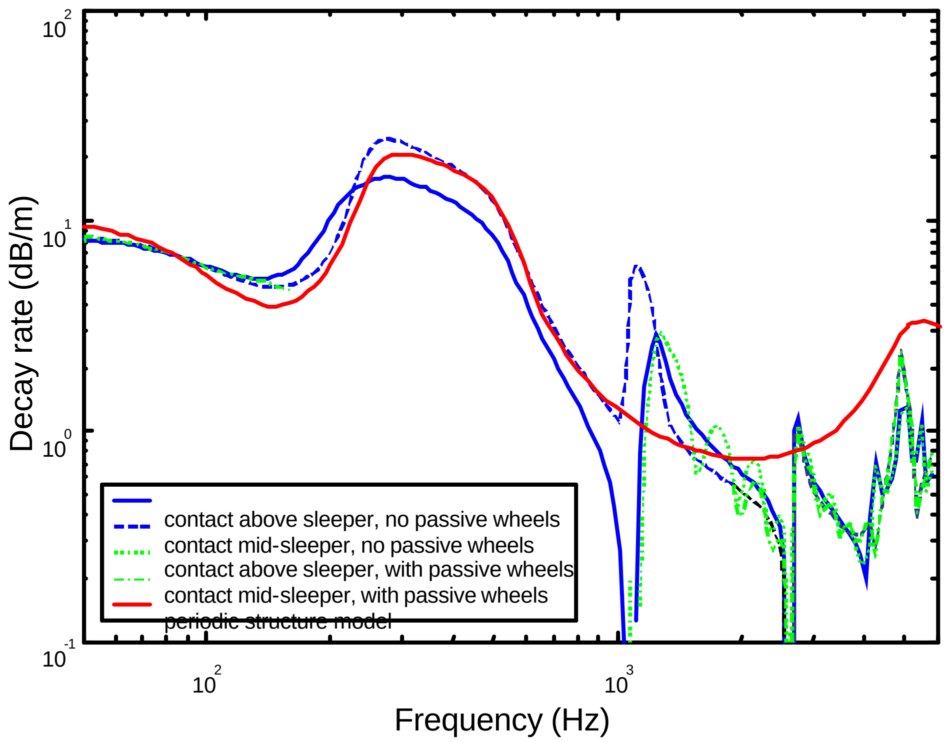


Figure 23. Vertical decay rates calculated using the periodic structure model and the new model.

Figure 23 presents an example of the decay rates calculated with the new model with regularly spaced sleepers. Results from TWINS's periodic structure theory model are also included. The track parameters correspond to those of Figure 22. The most significant feature is that the new model in addition to indicating a rise in decay rate to a peak around the cut-on of the foot-flapping wave at 5 kHz also shows a strong dip in the decay rates at the first and subsequent pinned-pinned resonance frequencies when the contact is above the sleeper and a peak for both contact positions a little above these frequencies. This has been observed in measurements but has not been shown previously in calculations. Its inclusion in theoretical analysis adds significantly the ability to understand acoustic track characterisation measurements.

Results which include the wheel reflection (Figure 23) show significant changes in the effective decay rate due to reflections at the passive wheel contacts. The decay rates generally are thereby increased.

The model can be used to investigate other effects such as the variation of pad and ballast stiffness with load along the track and the effects of irregularly spaced sleepers.

Use of the level 3 models in the STAIRRS programme

Within Workpackage 2 of STAIRRS, the level 3 model have been used in various pieces of work that supported the development of the measurement methods. These include:

- an assessment of various vehicles for possible use as a quiet reference for the measurement of track noise, [STR23TR300401ISVR1.doc],
- A study of the inherent variance of noise measurements due to the variability of vibro-acoustic parameters [STR23 TR240602ISVR2.doc.]
- A study of the sensitivity of the indirect roughness method to variations in track and wheel parameters [STR23TR030501ISVR1.doc].
- predictions of the vehicle and track transfer functions relating to the Caen measurement campaign [STR25TR240602ISVR1.doc]

The new track model is available to STAIRRS consortium members and is to be made more widely available through its inclusion in the TWINS software package.

2.2.2 Combining Separately Measured Vehicle and Track Components of Noise

One purpose of separation of vehicle and track roughnesses and transfer functions is to be able to predict the noise from a vehicle on a particular track based on the independently obtained separated quantities for that vehicle and track. The method can, however only be used if the following assumptions are adhered to.

- the train-speed dependence of $H_{pr,veh}(f_{to})$ [transfer function from combined effective roughness to wheel radiated noise] is negligible.
- the train-speed dependence of $H_{pr,tr}(f_{to})$ [transfer function from combined effective roughness to track radiated noise] is negligible.
- $H_{pr,veh}(f_{to})$ is independent of factors that may influence $H_{pr,tr}(f_{to})$
- $H_{pr,tr}(f_{to})$ is independent of factors that may influence $H_{pr,veh}(f_{to})$

Below are described a number of situations where the combining of data becomes inaccurate and should not be used.

Wheel size and load

The transfer functions and effective roughness are affected by changes in the wheel size and load and via effects of the *contact stiffness*, the *wheel mass* and the *contact filter*.

The wheel diameter and the wheel load affect the *contact stiffness* and this, in turn may affect the wheel and track transfer functions and thus the A-weighted noise level. Combining data from the literature and Hertzian contact theory allows estimations to be made of the change of wheel load and wheel diameter that would cause a 1 dB change in noise level.

For a 920 mm wheel with a load of 50 kN, a reduction of diameter to 150 mm or an increase to 4.5 m each cause a 1 dB change. There is therefore no realistic constraint, arising from the consideration of the effect of wheel size on contact stiffness from which transfer functions can be used in the calculation method with reasonable accuracy.

Wheel load changes from 50 kN down to 21.5 kN, or from 50 kN up to 128 kN, also each cause a 1 dB change in the noise level. This covers the range of the vast majority of wheel loads that may be encountered. Therefore unless the data from one extreme of wheel load is used for the opposite extreme prediction case, there is little constraint on the use of transfer functions implied by change of contact stiffness with wheel load.

In addition, it has been shown that *wheel mass* can have an effect on the track transfer function below about 500 Hz. However, a change of the wheel-set unsprung mass from 1200 kg down to 800 kg, or up to 2400 kg has an effect that is mostly less than 1 dB in the one-third octave bands above 100 Hz and can be neglected. If the wheel mass changes by more than this, the track transfer function will change appreciably and the method should not be used.

The effect of the *contact filter* on the *combined effective roughness* level is dependent on the diameter of the wheel and the wheel load. Thus, in order to use roughness data without correction for this effect, the diameter of the prediction wheel must not differ too much from that of the measurement situation of the selected combined effective roughness spectrum.

A criterion for this is that the cut-off frequency of the *contact filter* should not shift by more than one-sixth octave. This is also directly related to the length of the contact patch. Thus, for example, if the *combined effective roughness* has been measured using 920 mm wheels, the data should not be used for wheels smaller than 735 mm diameter or larger than 1180 mm. In addition to this criterion, the wheel load should not differ substantially as might be the case from passenger vehicles to freight vehicles or from two-axle vehicles to bogied vehicles. For the example of the 920 mm wheel, the cut-off frequency of the contact filter shifts by more than one-sixth octave if the load changes from 50 kN down to 35 kN or up to 70 kN.

In the case where the wheel diameter or load is outside the range for which the calculation can be directly applied, a correction to the prediction would have to be evaluated on the basis of a knowledge of contact patch and contact filter behaviour.

Noise reducing designs

The method relies on the assumption that the track transfer function is independent of the vehicle/wheel design and that the vehicle transfer function is independent of the track design. This assumption is expected to be valid, within a small error, for a wide range of existing vehicle and track designs and for many noise reduction measures *e.g., wheel damping, wheel shields* (*i.e. that screen only the wheel itself*), *rail damping, and novel rail fasteners*. The method is equally applicable to slab tracks, embedded rail tracks and tracks with unusual rail sections. However, there are some cases where this assumption is not valid. These include:

Resilient wheels

When resilient wheels are used, the rail noise is dependent to a much greater extent on the design of the wheel than for conventional wheels. Thus the track transfer function is affected by the use of the resilient wheel.

Low level acoustic screening

Systems of close, low noise barriers on the track together with noise screens mounted around the bogies of the vehicle have been proposed for noise reduction. Such a track barrier affects both the wheel-radiated noise and the track radiated noise but, because of the differing heights of the sources in comparison to the close barrier, the effect on each transfer function is different.

Bogie shields screen the wheel noise but their presence, both as a noise barrier and as an acoustic cavity with sound absorption, close to the sleepers and rails, also affects the track noise.

The effects of shields and barriers may be modelled separately either using proprietary software or with a special module of the TWINS package to determine their effect on the vehicle noise and track noise separately.

2.2.3 Measurement Procedure for Separation Techniques

The following measurement procedure has been developed to provide data for the separation techniques described in Section 2.2.1.

In order to obtain a complete set of data for the database, a number of additional parameters should be measured. These parameters are listed in this procedure as well.

Transducer Location

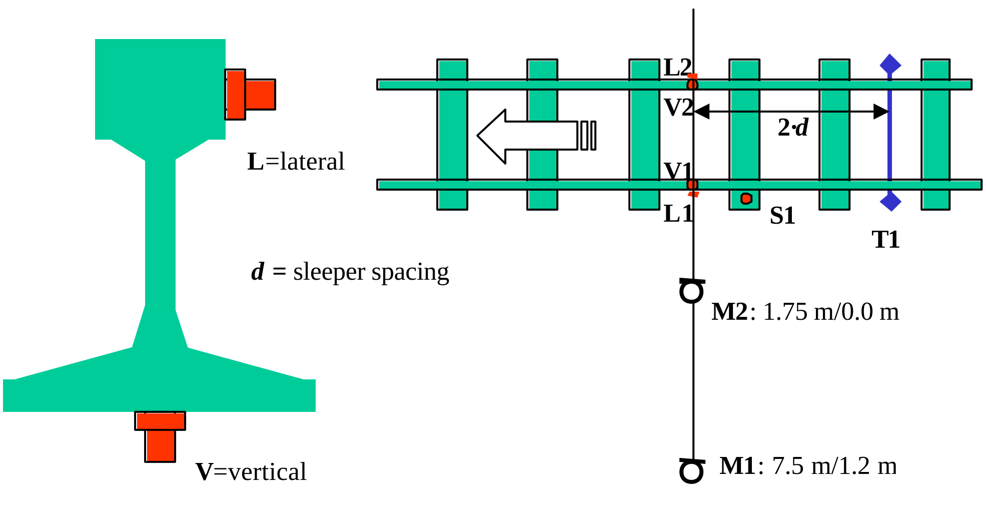


Figure 24: Position of transducers on the track.

Two lateral and two vertical accelerometers are needed (L1, V1,L2,V2). The two lateral ones are placed on one side of the railhead and the vertical ones under the railfoot, all at midspan (midway between two sleepers, see Figure 24). One more vertical accelerometer S1 is placed on the sleeper close to the rail fastener.

Slab track: if there is not enough space to fit V1 and V2 under the railfoot, it is allowed to fix these accelerometers on top of the railfoot, as close as possible to the centre. S1 should be placed between the fasteners, at about 1/3 of the slab length and 1/3 of the slab width.

Microphones positions (distance from centre of track / height above railhead):

M1: 7.5m/1.2m

M2: 1.75m/0.0m

One Trigger or treadle (T1): 2 sleeper spacings away from the cross section, upstream (the blue line in Figure 17).

High pass filter

To ensure that the near field microphone(M2) is not overloaded AND that the dynamic range of the acquisition is sufficient over the whole frequency range it is highly recommended to use a high pass filter between the transducer and recorder (for trains speeds below 200 km/h, the cut-off frequency should be 80 Hz. For speeds above 200 km/h it should be 150 Hz).

In the case where a high pass filter is used for M2, the same filter must also be used for the accelerometers (at least V1 and L1) in order to compensate the time delays introduced between those transducers.

Choice between tools

In order to add data to the database, analysis with tool 1 (PBA) is required, while tool 2 (MISO) and 3 (VTN) are interchangeable. This means that the user is free to choose between VTN and MISO for separation. However, the STAIRRS measurement procedure requires that **all signals be measured using a highpass filter** on M2, and accelerometers (at least L1 and V1). The following table lists the signals that are required, per tool.

tool	developer	M1	M2	L1	L2	V1	V2	T1	S1	Highpass filter	
										M2, L1, V1	L2, V2, S1
PBA	TNO	++	-	++	+	++	+	+		O	O
MISO	SNCF	++	++	++	o	++	o	++	o	++	O
VTN	AEAT	++	-	++	+	++	+	+		O	O

++ = required

+ = recommended

o = optional

- = not used

Signal specifications

Noise and vibration signal bandwidth: 10 Hz to at least 7.5 kHz, but preferably 10 kHz. Due to the high-pass filter applied to signals M2, L1 and V1, the bandwidth used for these signals is slightly smaller. Minimal Effective dynamic range: 40 dB.

Trigger signal: TTL-like pulse at each wheel passby, same bandwidth as above.

Noise, vibration and trigger signal must be of equal length, recorded simultaneously and synchronously on the same analyser. Signal length, however, may vary between pass-bys. The complete train pass-by must be taken, inclusive of a few seconds of background noise before and after the pass-by.

Signal file format

Raw signals should preferably be stored in MATLAB mat-files, or otherwise ASCII-files. For each train pass-by 8 files must be delivered:

2 sound pressure signals with reference [1 Pa]

5 acceleration signals with reference [1 ms^{-2}]

1 trigger signal with maximum normalised to unity.

Contents of mat-files

```
Name      Size      Bytes     Class
comment   1x102     204       char array     (optional) channel description; length may vary
data      690000x1  5520000   double array   signal itself; columnwise; length may vary
dt        1x1       8         double array   sample period [s]
```

Alternatively: contents of ASCII-files

The first line is a header, its first 7 digits are reserved for the sample period in seconds, ending with a tab. The rest of first line may be text (e.g., channel description). Data are written in a single column.

File names

A file must be named as stated here :

- file names are in 8 digits + extension;
- digit 1 and 2 are channel descriptor (M1, M2, T1, S1, L1, V1, L2 or V2);
- digit 3 is underscore;
- digit 4, 5, 6 is the pass-by number (preceeded by zeros as in example below);
- free digit 7 and 8 may contain additional information.

Example**: `M1_008.mat`** (or, if it's an ASCII file, `M1_008.txt`)

Measurement information

Site information

Country, nearby village, line (from/to), track identifier (code in case of >1 track), mile-code or km-code, type of rail, type of pad, type of fastening, type of sleeper (wood, mono-block, bi-block, slab track, ...), nominal sleeper spacing, trigger distance (if other than twice the sleeper spacing), video recording or picture with overview of the site and accelerometer positions.

Train information per pass-by

A type of train identified by a 7 digit label as described below in Table ? Additionally the following information is required:

train speed [km/h],

train composition,

train running direction (if reversed),

time of pass-by,

rail temperature (precision ± 5 ºC).

A video recording should be made of all freight trains and of those trains measured at two sites (on the same day or service).

Train Label format

digit:	1	2	3	4	5	6	7
descriptor	**train type**	**# axles per vehicle**	**length of vehicle**	**vehicle type**	**load**	**wheel diameter**	**brake type**
how it is encoded	type of the train	the actual number of axles	length between buffers	letter that describes the type	freight vehicle load	the class of diameter	a letter that describes the brake type
codes allowed	**O** Other (i.e. maintenance vehicles...)	**u** unknown	**u** unknown	**u** unknown	**u** unknown, use also u for passenger and locos	**u** unknown	**u** unknown
	H High speed passenger	**1**	**l** long, >20m	**m** multiple unit passenger coaches	**l** loaded freight	**l** large, >800 mm	**c** cast-iron
	P conventional Passenger	**2**	**m** medium, 12 to 20 m	**p** pulled passenger coaches	**n** not loaded freight	**m** medium, 500 to 800 mm	**k** k-block
	F Freight	**3**	**s** short <12 m	**d** diesel loco		**s** small < 500 mm	**n** non tread braked, like disc, drum ,...
	L Loco	**4**		**e** electric loco			
		et cetera		E,F,G,H,I, K,L,O,R,S,T,U ,Z UIC-designation for freight vehicles			

Circumstances

Date, wind speed, air temperature (range over period of measurement).

Procedure for roughness measurements

The rail roughness at the measurement site should be measured directly, according to prEN ISO 3095. The roughness spectrum should be determined with a reference of 1 µm. The wavelength range is 0.5 cm to 20 cm. The roughness measurement equipment should use a contacting transducer. Accuracy and S/N-ratio of the system should be such that compliance with the limit spectrum mentioned in the ISO standard can be measured reliably.

The one-third octave band spectra should be delivered in Excel (named 'railroughness.xls') with the following format.

Wavelength (cm)	20	16	12.5	10	8	...	...	0.63	0.5
Rail roughness (dB re 1 E-6 m)	17.7	15.7	10.9	6.7	3.6	...	...	-7.0	-5.8

Long wavelength with RM1200E and ØDS TRM01

With these instruments only a wavelength range 0.1 cm to 10 cm can be achieved with reasonable accuracy, due to their measurement length of 1.2 m. In order to extend the wavelength range, the ISO 3095 procedure is slightly changed and a concatenation procedure is used during post-processing. A full description of the procedure and procedure is given in STAIRRS Deliverable 11 part 4 *Direct roughness measurements and Vibro-acoustic Track Noise method* (ref. STR23TR130902AEA1). Here, only the required extension of the ISO 3095 procedure is treated, see Figure 25. The two central sections "3" and "4" of the ISO-procedure are shifted 10 cm towards each other in order to obtain 20 cm overlap. Besides this, an additional section should be measured at either side of the two central ones, overlapping the central ones by 20 cm. This yields four subsequent, overlapping profile lines in the centre of the site.

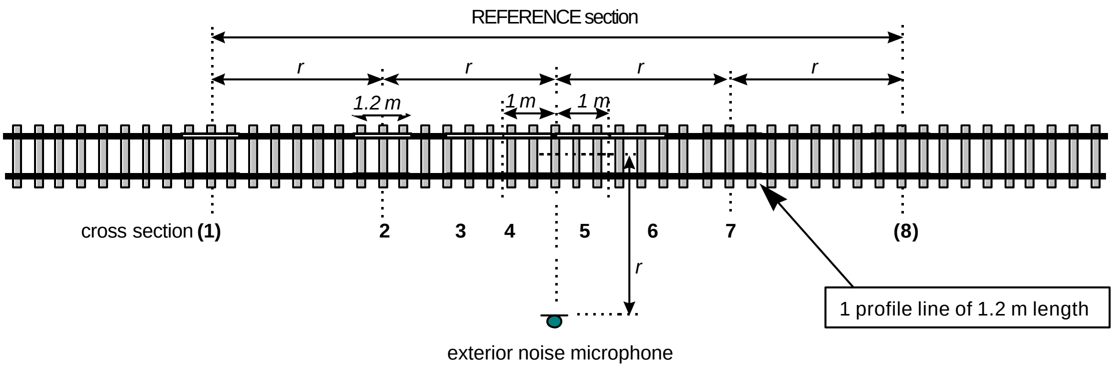


Figure 25: Required procedure for rail roughness measurement with instruments of 1.2 m length.

Summary of deliverables per campaign

1. CD ROM with 8 data files per pass-by.
2. Excel file with measurement information and roughness spectrum, format given in Chapter 0.
3. Video cassette showing pass-by of freight trains.
4. Picture or video recording showing site overview and accelerometer positions.

Format of STAIRRS Excel form

STAIRRS Excel form was developed to collect all the data acquired during several measurement campaigns, allowing the user to introduce roughness, sound pressure and vibration data acquired in different ways and with a more or less complete set of those data. An empty STAIRRS Excel form can be obtained for free at AEA Technology Rail BV.

This tool was created for the following reasons:

- Microsoft Excel files can be opened interactively and the required data can easily be input by measuring teams
- data can easily be stored using the *STAIRRS Database* program;
- links to Microsoft Access files can be made to store data.

There are several ways of introducing data from measurements, at the same time there are several ways of interpreting data and several needs for different sets of data. The present Excel file is a compromise between all those needs, that require not much work to introduce a great quantity of data. With the help of the present manual, it should be a simple matter to fill in data.

Understanding the "ExampleFormat.xls" structure

The ExampleFormat.xls file must be used as a template to modify by introducing the right data. This Excel file is composed of required sheets and sheets that can be added when necessary (there is no maximum sheet number).

Here is the list of those sheets:

general information

conventions

measurement setup

site description

train composition

vehicle info

pass-by list

pass-by data 1a_06

pass-by data 1a_10

pass-by data 2_1

pass-by data 2_.

The first seven sheets contain general information about the team, the site, the train, the pass-by,… The last sheets (and all the sheets which name begin with "Pass-by data") will contain each pass-by measured spectrum.

All the cells have four different colours, each having a special meaning:

Green	Information to introduce correctly all the fields: these cells must not be modified by the user
Light yellow	Contain fields that usually the user can decide whether to fill in or not. This depends usually on information available and values recorded during the measurement campaign (e.g., a team can have accelerometers while another team may not).
Dark yellow	ALL these fields MUST be entered by the user, or the STAIRRS Database will not run properly
Red	These fields require special attention from the user, but they are not used in the database

Entering the correct information

General information

In this sheet "project name" and "measurement team" are the fields that must be filled in.

Conventions

This sheet contains general information about reference levels and more. Its purpose is to provide instructions before entering data.

Measurement setup

This sheet illustrates how to set the microphones and accelerometers on the measurement site. Its purpose is to provide instructions before entering data.

Site description

A unique reference name for the site must be entered here, then some more information about the track type, sleeper, etc. is requested but its input is not essential.

Note: the cell "inclination" should contain only the denominator of the fraction that defines rail inclination.

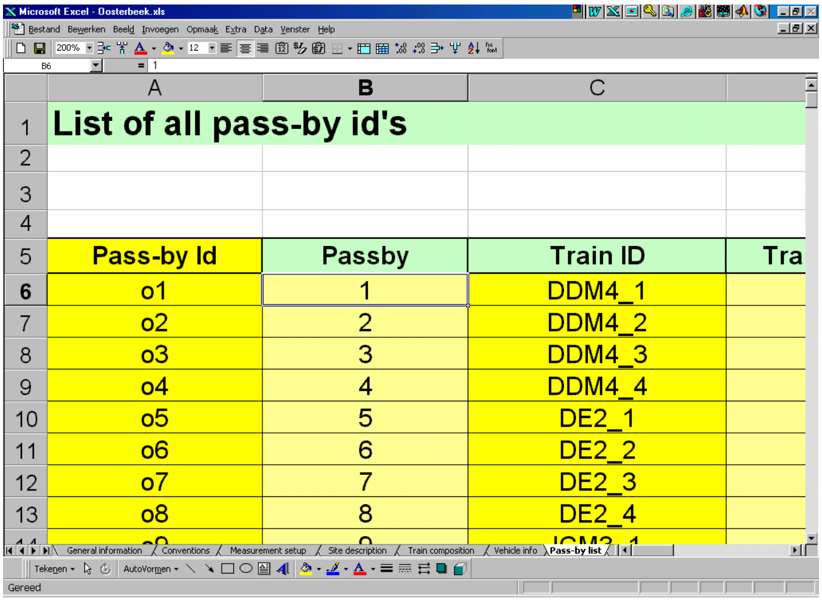
Train composition

This sheet is a picture that provides help to the user showing all the parameters of the train. It has no other function.

Pass-by list

In the first column the user must introduce a **unique reference name for the measured pass-bys**, then indicate the **measured train** in the third column. These two fields must be filled in or the Excel file will be invalid. These two fields must be consistent with the same fields found in the "Vehicle info" sheet and each existing "Pass-by data XXXXX" sheet, where XXXXX stands for each "pass by id" introduced in the "Pass-by list"sheet .

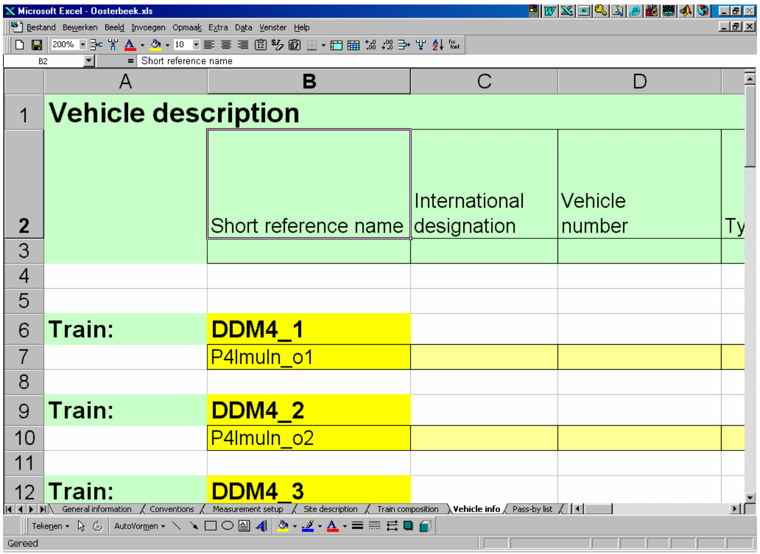
Other fields that the user may fill in are the number of the pass-by, if the same train passed the same site several times, then the train orientation, direction, etc.



Vehicle info

In the second column the user must enter all the trains that were measured, that is to say at least one. The simplest way to fill in this sheet is to have only one kind of train, that is a general train with unknown vehicle types and an unknown vehicle number. If this is the case, the user can use any name for the train field (e.g., on the cell B6, at the right side of "Train"), then specify that there is only one vehicle type/group, introducing "General" in the cell under "General Train".

Note: a train name (cell at the right of "Train" field) and at least one vehicle type must be set after each "Train" field present in the first column (e.g., if two "Train" words are found in the first column, at least two train names and two vehicle types must be present on the second column). Train names must be the same as introduced in "Pass-by list" sheet, vehicles must be the same as found in the correlated "Pass-by data XXXXX" sheet (see also Section If the user knows more about the vehicles, there are several fields than can be filled in, and different vehicle or vehicle group names can be set after the line with the train name. All the vehicle (group) names present in the corresponding "Pass-by data XXXXX" sheet must be present. These names should be in accordance with the Vehicle label format. Blank lines between one "Train" field line and the next one are not a problem for the STAIRRS database.



Pass-by data XXXXX

This sheet occurs at least one time, but can occur many times: each pass by should have its own "Pass-By data XXXXX" sheet, where XXXXX stands for the name of the pass-by as set in the "Pass-by list".

The same name must be filled in the "Pass-by data/site data"field on the first line, then at least the train speed must be filled.

All the measured data will be filled in. This table shows all the fields, specifying all the compulsory ones.

The user must introduce as many "Vehicle / group or vehicles identity" fields (with all the related values) as the number of vehicle groups of the measured pass-by.

Quantity	**Compulsory**	**Notes**
Rail vertical decay rate (-)		
Rail lateral decay rate (-)		
Rail roughness (re 1 E-6 m)		
Vehicle / group or vehicles identity	Yes	1.
Wheel roughness (re 1 E-6 m)		
Contact filter (re [-])		
Total effective roughness (re 1 E-6 m)		
SPL overall level (1.75 m, 0.0 m) (re 2 E-5 Pa)	Yes	2.
SPL overall level (7.5 m, 1.2 m) (re 2 E-5 Pa)	Yes	2.
SPL vehicle contribution (7.5 m, 1.2 m) (re 2 E-5 Pa)		
SPL track contribution (7.5 m, 1.2 m) (re 2 E-5 Pa)		
Rail vertical vibration level (re 1 E-6 m/s)		
Rail lateral vibration level (re 1 E-6 m/s)		

Quantity	Compulsory	Notes
Sleeper vertical vibration level (re 1 E-6 m/s)		
Vehicle axles per metre correction 10*LOG10(N/L) (re [-])	Yes	3.
Vehicle transfer function (re [-])		4.
Track transfer function (re [-])		4.
Overall transfer function (re [-])		4.

1. The number and the name of the vehicles must be the same as set in the "Vehicle info" sheet.

2. Some one-third octave frequency bands can be omitted, the STAIRRS database will still run.

3. If the user knows the vehicle characteristics, the correct number must be introduced, this being 10*$\log_{10}$(number of axles / vehicle length), if an unknown train is measured, then the default value of –8.0 must be set. This number is obviously the same for all frequencies.

4. The transfer function to be entered is the one defined by the STAIRRS project, namely:

$$H = L_p - L_r - CF - 10 \cdot {}^{10}\log(N/L)$$

where:

Lp = sound pressure level in dB re [20 µPa], of vehicle, of track or of total;

Lr = combined direct roughness dB re [1µm];

CF = contact filter dB re[-];

N = number of axes per vehicle;

L = length of vehicle.

The existing sheets present examples of different possibilities:

pass-by data 1a_06 – train and vehicles are known and rail and wheel roughness are all known;

pass-by data 1a_10 – train and vehicles are known, but only some measurements are available, roughnesses are unknown;

pass-by data 2_1 – a group of a certain kind of vehicles can be recognized, but the first part of the train cannot, so there is a set of data for a general vehicle type and a set of data for the ICM50 vehicle type.

pass-by data 2_2 – nothing is known about the measured train, only sound pressure measurements are taken.

2.2.4 Measurement Campaign and Data base

In order to (a) test the validity of the techniques developed and (b) commence inputting data into a railway noise data base a number of measurement campaigns were mounted in France, The Netherlands, Austria and Italy.

The separation techniques, measurement procedures and data base structure were tested at three sites (Oosterbeek, Prinzersdorf and Caen) in 2001. This included measurements at the

Caen site by the teams from SNCF, TNO and AEA Technology Rail bv to compare their separation techniques. This comparison is shown in Figure 26 where it is seen that although there are differences in the detail of the separated levels obtained from each technique, when carrying out a broad comparison to indicate which, if either, of the vehicle or track is the dominant source, the techniques give a consistent answer. This gives confidence in using any of the separation techniques to indicate where noise reduction measures should be applied.

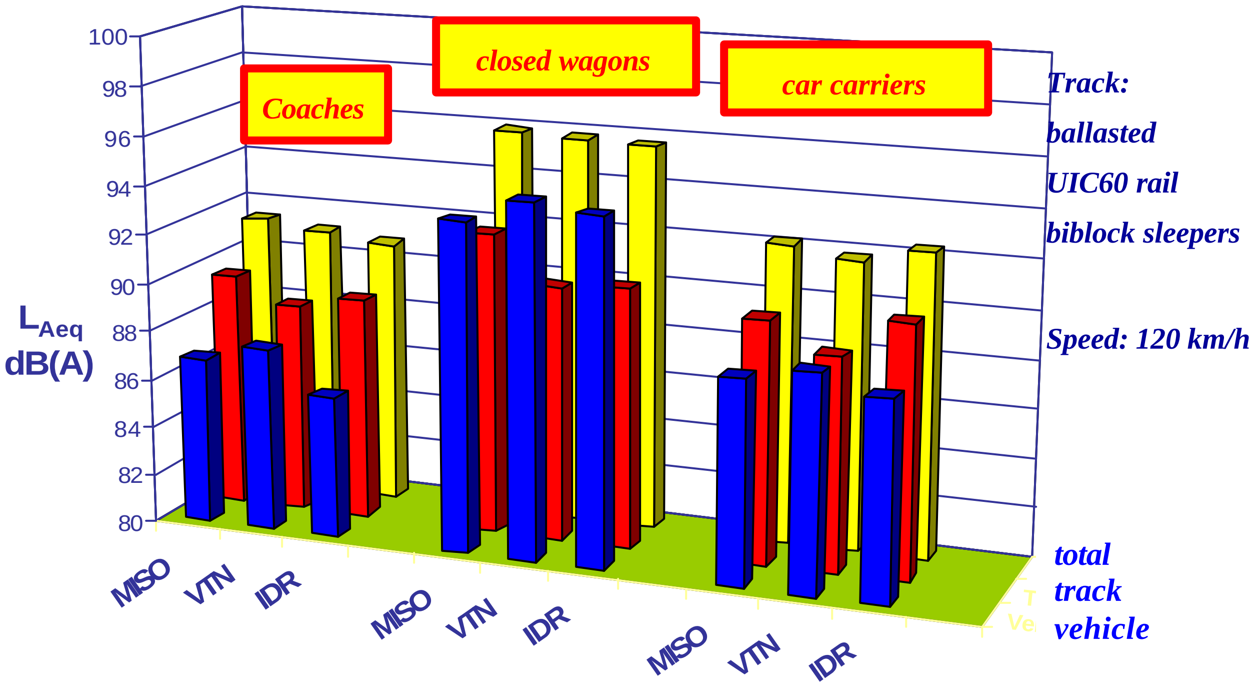


Figure 26: Comparison of MISO, VTN and PBA on Standard Track

Additionally, from the measurements at these sites a revised roughness measurement procedure was developed (section 2.2.5) and the structure of the data base was revised.

Thus these measurements gave confidence that the separation techniques were consistent and valid and that the measurement procedures could be applied to the full measurement campaign which was carried out in Spring 2002. The sites were Willemsdorp (Netherlands), Chambery (France), one site North of Paris on the Paris - Lille route (France), and two sites in Italy (Venzone and Gemona on the Udine -Tarviso route and S. Ambrogio on the Turin - Modane route). Trains at these sites included 2, 3, 4 and 6 axled freight, conventional passenger, high speed passenger and locomotives.

Analysis of the data was carried out for a number of passbys and the results added to the data base using the formatting in section 2.2.3.

A complete record in addition to descriptive information of the vehicle, track, site, climatic conditions, train operating conditions etc contains the following quantities

overall noise level @ 7.5m (dBlin and dB(A))

vehicle contribution to overall noise level @ 7.5m (dBlin and dB(A))

track contribution to overall noise level @ 7.5m (dBlin and dB(A))

overall noise level @1.75m (dBlin and dB(A))

overall noise level @ 25m (dBlin and dB(A))

1/3 octave band noise levels (25 Hz - 10 kHz) for each of the above quantities

1/3 octave band levels (25 Hz - 10 kHz) for each of the following quantities

rail lateral vibration

rail vertical vibration

sleeper vertical vibration

wheel roughness

rail roughness

total effective roughness

rail vertical vibration decay rate

rail lateral vibration decay rate

vehicle transfer function

track transfer function

overall transfer function

contact filter

Additionally

Vehicle axles per metre correction.

Currently the data base holds more than 3000 separate records although not all the quantities above are available for each train record.

2.2.5 Improvements to procedure for rail roughness measurements

2.2.5.1 Introduction

Rail roughness varies along the track, causing noise level variations of up to 15 dB(A). Wheel roughness varies between different trains, and is responsible for noise level differences as large as 8 dB(A).

Rail and wheel roughness can be measured in a several ways. The measurement methods can be divided into *direct* and *indirect* methods.

Direct method: a measurement procedure in which the rail and wheel surface are scanned directly and separately. The most frequently used systems employ displacement transducers or accelerometers in sensors that touch the rail or wheel surface. Several types of instruments have become commercially available in the past decade.

Indirect method: a measurement procedure in which the total effective roughness of rail and wheel are determined. Indirect measurements are carried out either on-board a running train (using axlebox accelerometers or bogie microphones), or at the track by measuring rail vibrations during train pass-bys. Indirect measurement methods are being explored and established elsewhere within STAIRRS WP2.3.

Direct methods can distinguish between rail and wheel roughness, which make it possible to apportion responsibility for corrugated tracks or rough wheels to track owners and vehicle owners. Indirect methods do not have this advantage, unless very smooth wheels or rails with known roughness are used. On the other hand, indirect methods measure the actual roughness ‘felt’ by the wheel/rail contact, hence the roughness excitation itself. Direct methods have limited accuracy in determining the total effective roughness due to the uncertainty in the wheel/rail contact filter effect.

In this section, the direct measurement methods for rail roughness are discussed. Also, the measurement procedure of the ISO 3095 norm is discussed and proposals for improvement are given.

2.2.5.2 ISO-procedure

Rail roughness measurements have been standardized in the international standard for type testing of exterior noise of rail vehicles, pr EN ISO 3095:2001. The measurement procedure described therein is developed in parallel with the METARAIL project.

The following limitations of measuring with stationary instruments of 1.2 m length, like RM1200E (Müller-BBM) and TRM01 (ØDS-Caltronic), will be discussed:
- The ISO-procedure demands measuring 36 profile lines. The necessity of measuring that amount of lines is investigated: a good balance between the accuracy needed and the amount of measuring work is desirable.
- The wavelength range of the roughness spectrum that can be achieved is approximately 0.5 cm to 10 cm. The longest wavelength is the one-third octave band in which at least 3 narrow band spectral lines are found (here 10 cm). With this bandwidth, the roughness excitation of high speed trains cannot be calculated to a satisfactory degree. A procedure to extend this bandwidth is needed.

The ISO-procedure requires altogether 36 profile lines to be measured, see Figure 27.

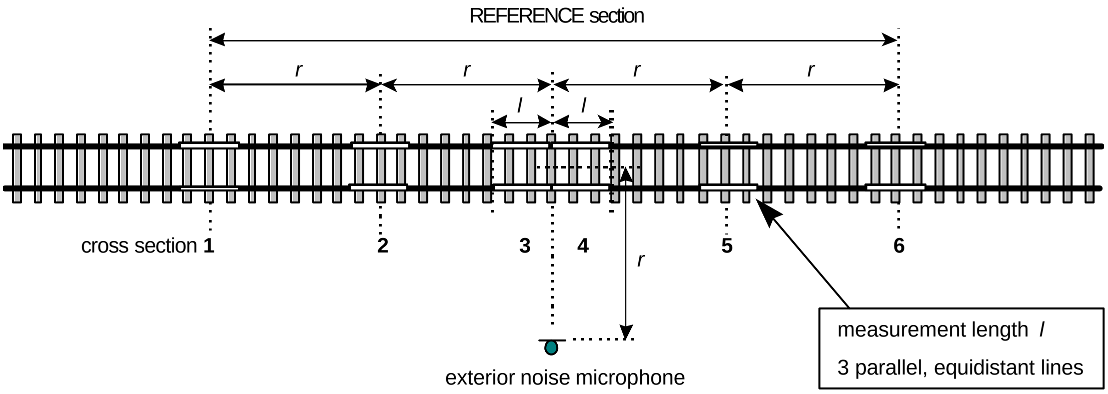


Figure 27: Measurement map for rail roughness

At each of the 6 sections, 3 parallel lines on both rails should be measured. The irregular spacing between the sections (section 3 and 4 are adjacent) is the result of a compromise between two points of view. One point of view assumed that the rolling noise measured is proportional to the average rail (and wheel) roughness if this average takes into account the distance between the sections and the exterior noise microphone (for that reason this procedure originally required only one line to be measured at the farthest section 1 and 6). The other point of view assumed that a representative roughness spectrum should be an average of many parallel lines and many sections. In the following discussion, proposals for improvements will be given that still keep both principles in mind.

2.2.5.3 Lateral position on the railhead

The ISO 3095 procedure gives the following description of the lateral position on the railhead were the profile lines should be measured.

Rail roughness shall be measured on a line in the centre of the running band. If the running band is wide enough, two supplementary parallel, equidistant lines at either side of the centre line must be measured. The distance between the centre of the running band and the supplementary measurement lines depends on the width of the running band:

- running band width <= 10 mm: measurement of 1 line;

- 10 mm < running band width <= 20 mm: measurement of 3 lines, 5 mm equidistant;

- running band width > 20 mm: measurement of 3 lines, 10 mm equidistant.

The purpose of measuring 3 parallel lines is to obtain a representative impression of the roughness, minimizing the error between direct roughness and effective roughness ('felt' by the wheel/rail contact). At the time of issuing the draft ISO-procedure, only little knowledge was available about the variation that occurs laterally across the running band. During 3 years of experimenting with the procedure, it was noticed that on most tracks the lateral variation of roughness is rather small. The necessity of measuring three lines is therefore reconsidered here.

To check this necessity, two averages were calculated for a number of sites[4]. Analysis of that data showed the minimum and maximum level occurring in each one-third octave band and it was observed that:

a. the site average spectrum as calculated in both ways is comparable;
b. the site spread is largely caused by variations along the rail, rather than laterally across the railhead.

Observation *a* is confirmed by $L_{\lambda CA}$-calculations of the averages. The difference in $L_{\lambda CA}$ between both types of averages are smaller than 1 dB per site. In fact, for 5 sites the differences are even smaller than 0.5 dB. Also, no significant systematic difference between both types of averages is found, as the average difference between both types of averaging is 0.1 dB.

From this it is concluded that measuring one line at the centre of the running band will in many cases suffice for the purpose of estimating a site average direct roughness spectrum. Two exceptions to this rule will be discussed here. The first exception copes with situations where more than one running band is visible. The second exception deals with extraordinarily wide running bands.

Two running bands

On the Oosterbeek track, during the STAIRRS measurement campaign of 4 and 5 July 2001, *two* parallel running bands were spotted instead of one. The track had been ground a few weeks before the measurement. Figure 28 demonstrates these bands. It shows 5 parallel profile lines laterally spaced 5 mm on the railhead. The vertical axis in the graph has been offset in steps of 20 µm for clarity. The lowest line is taken at the smooth inner running band, the two highest lines are measured at the rougher outer running band. As the intermediate lines clearly show grinding grooves while the others do not, it can be concluded that most wheels will not follow the intermediate band.

In such a situation roughness characterisation using the direct measurement procedure is problematic. The ISO-procedure cannot be applied unambiguously here. Different measurement teams may identify different running surfaces. For the above case, this may lead

[4] Sites Schalkwijk, Savigliano and Wiener Neustadt were measured during the METARAIL Round Robin Campaign (1998), site Croydon (1999) is a tramway track in South-London, site DE-track and DE-bridge are measured near Utrecht (2002).

to spectral differences (in the main one-third octave bands) as high as 5 dB, which is considered unacceptable.

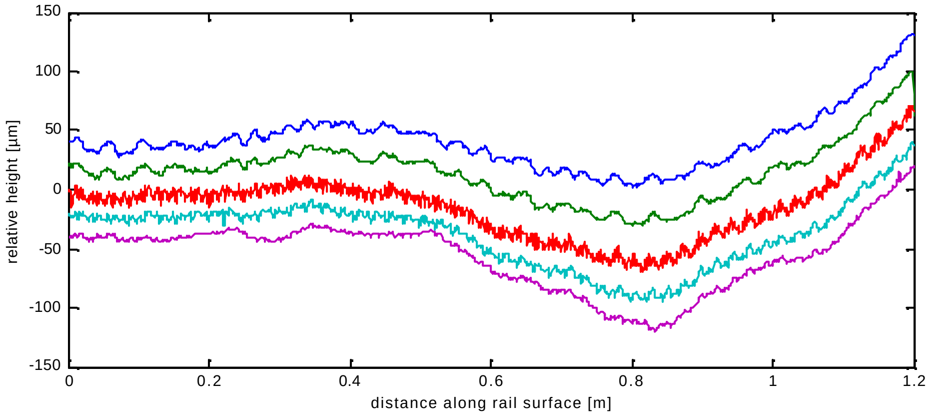


Figure 28: Oosterbeek track.: 5 parallel profile lines, lateral offset on the railhead –10, -5, 0, 5 and 10 mm, respectively.

Extraordinary wide running band

A similar problem occurs if an extraordinarily wide running band (e.g. > 3 cm) is encountered by the measuring team. Once again it is not clear then where the wheels actually touch the rail head, while due to the width of the band a significant difference in roughness may exist between either ends of the running band.

It can be concluded that measuring more than one (parallel) line is not appropriate in most cases. Only if two running bands or an extremely wide running band is found, should more lines be measured. Section 2.2.5.6 gives a measurement procedure that accounts for these phenomena.

2.2.5.4 Number of sections

The number of sections in the ISO-procedure is 6. The site average rail roughness is calculated as the energy average of those 6 section averages. The goal of this paragraph is to find out whether the number of sections in the procedure is appropriate for the calculation of a representative site average. Therefore, the sensitivity of the site average for the number of sections is investigated.

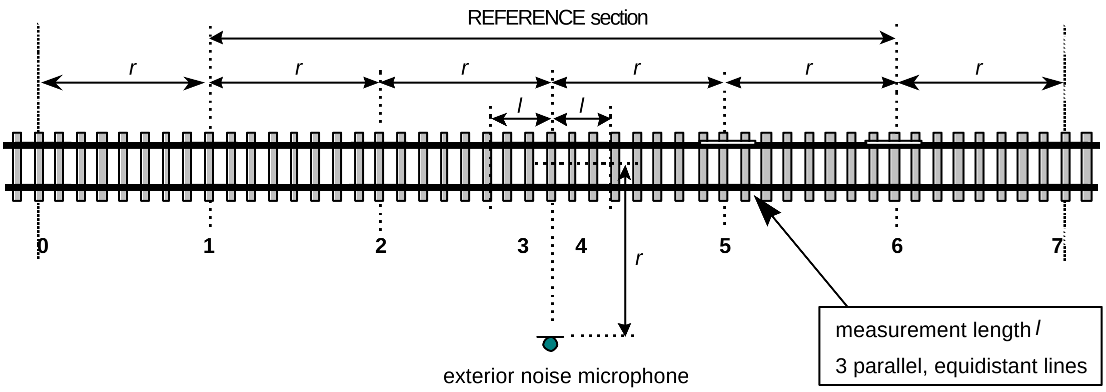


Figure 29: ISO procedure, with extended sections 0 and 7.

For this purpose, the ISO-procedure (Figure 29) has been extended with section 0 (to the left of section 1) and section 7 (to the right of section 6). Next, the site average can be calculated for 8 sections (section 0 to 7), 6 sections (section 1 to 6) and 4 sections (section 2 to 5), respectively. This exercise was carried out for 4 different measurement sites[5]. It was observed that the maximum and minimum per one-third octave band do not depend strongly on the number of sections taken into account: some of the extremes per one-third octave band are (almost) equal for 8, 6 or 4 sections.

To check the sensistivity of the site average, also the $L_{\lambda CA}$ at 100 km/h has been calculated for the site averages. Going from an average of 8 sections down to 6 sections will lead to changes up to 0.3 dB for the $L_{\lambda CA}$. Reducing the number of sections from 8 to 4, yields changes up to 0.6 dB.

The small changes in spread of the extremes and the small changes (<1 dB) in $L_{\lambda CA}$ point out that the site average is not very sensitive to the number of sections included. Extending the procedure to 8 sections does not lead to a better defined site average. Also, reducing the number of sections to 4 still gives a fair estimate of the site average. However, in order to be able to identify possible extreme differences between the sections, it is proposed not to decrease the number of sections from 6 to 4. The 6 sections from the ISO-procedure cover a range of 30 m (for noise measurements at 7.5 m from the track), which seems a fair range compared to a range of only 15 m in case of 4 sections.

Therefore the following is concluded:

- For type testing purposes, where it is usually possible to select a measurement track and site on a 'thin' line (few trains per hour), the number of 6 sections to be measured and averaged should be maintained.
- On extremely busy ('thick') lines, where track access of only a few minutes is already a difficult job, it is acceptable to measure only 4 sections. However, it should be assured by visual inspection that the site does not show spots with deviating roughness within a range of at least 30 m. This gives the measuring team the possibility to use a feasible roughness measurement procedure similar to the one of the ISO-norm outside the scope of type testing.

2.2.5.5 Long wavelength range

The wavelength range of the roughness spectrum depends on the profile length. For roughness instruments that measure 1.2 m of rail, the longest wavelength that can be determined with reasonable accuracy is about 10 cm. For high speed applications longer waves are needed to assess the influence of rail roughness on rolling noise. First the required wavelength range is determined, then a procedure to extend the wavelength range is described. These findings, including those of the previous section, will be combined in a new proposal for rail roughness measurements.

Wavelength range

The draft ISO-procedure is ambiguous in stating the requirements for the wavelength range. In Figure 4 of the main body text of the norm a range of 0 to 60 cm is suggested for speeds between 60 and 200 km/h, while in (normative) annex D.3 a range of 1 to 8 cm is declared appropriate for site approval (without speed specification). Clearly, the wide range (0 to 60

[5] Sites Schalkwijk, Savigliano and Wiener Neustadt were measured during the METARAIL Round Robin Campaign (1998), site Croydon (1999) is a tramway track in South-London.

cm) accounts for the whole noise spectrum range, while the short range includes only those bands that contribute most to the A-weighted noise spectrum. In this report a range extension up to 31.5 cm will be assumed appropriate for most train speeds. At 300 km/h this roughness wavelength corresponds to about 260 Hz.

Measurement procedure

The wavelength range can be extended by composing an elongated roughness profile out of separate, consecutive lines of 1.2 m length. In order to be able to concatenate these lines during post-processing, an overlap of 20 cm (± 2 cm) should be taken during measurement, see Figure 30.

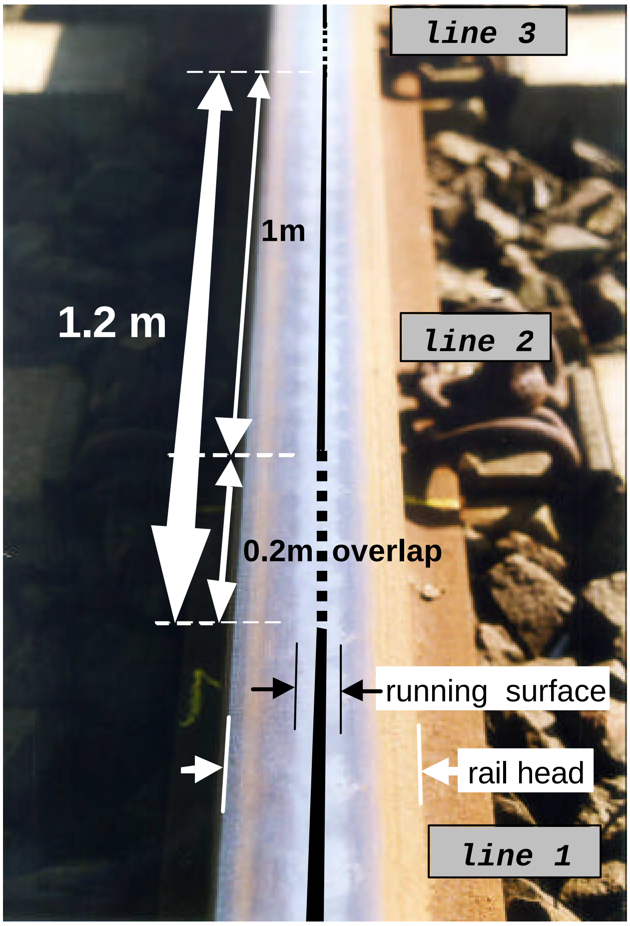


Figure 30: Consecutive roughness profiles.

In order to cover a wavelength range of 31.5 cm, the length of the (concatenated) profile should be 4.2 m. In that case, at least 3 FFT-lines are present in the 31.5 cm wavelength band (bandwidth one-third octave).

Concatenation procedure

A Matlab-program has been written to carry out the concatenation. For each new profile line to be concatenated to the previous one, the following procedure takes place. The end of the previous line is displayed together with the start of the new line, assuming exactly 20 cm overlap. The tilt angle in the overlap zone is removed in both signal ends. This is shown in Figure 31.

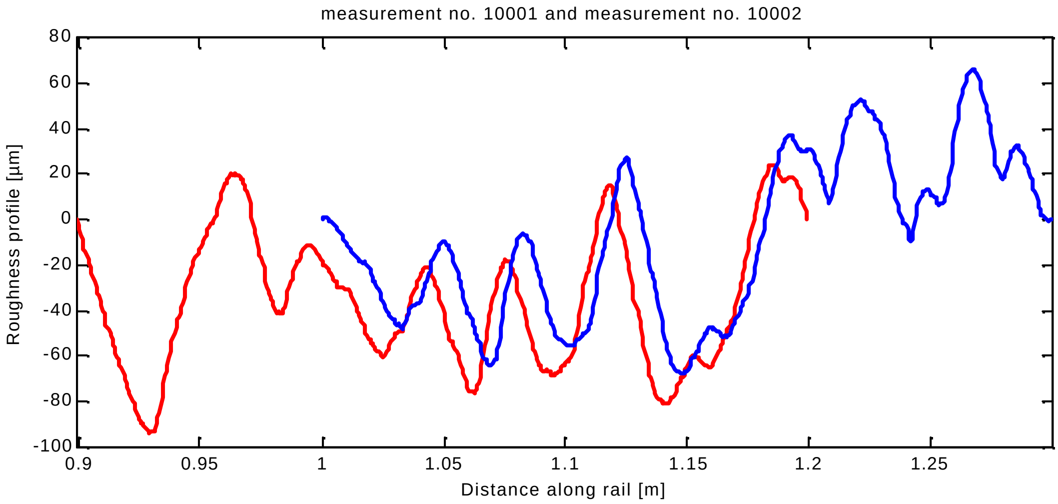


Figure 31: Fitting procedure. At start, data is displayed assuming exactly 20 cm overlap.

In order to align the new (blue) line, this line can be shifted stepwise manually. Clearly the example shown in the figure should be moved left. Once the proper horizontal offset is found, the user can proceed manually or automatically in moving the new line in the vertical direction and applying a tilt. The automatic mode uses least squares fitting and gives proper results in the case of visibly good correlation between the profile ends to be matched (Figure 32).

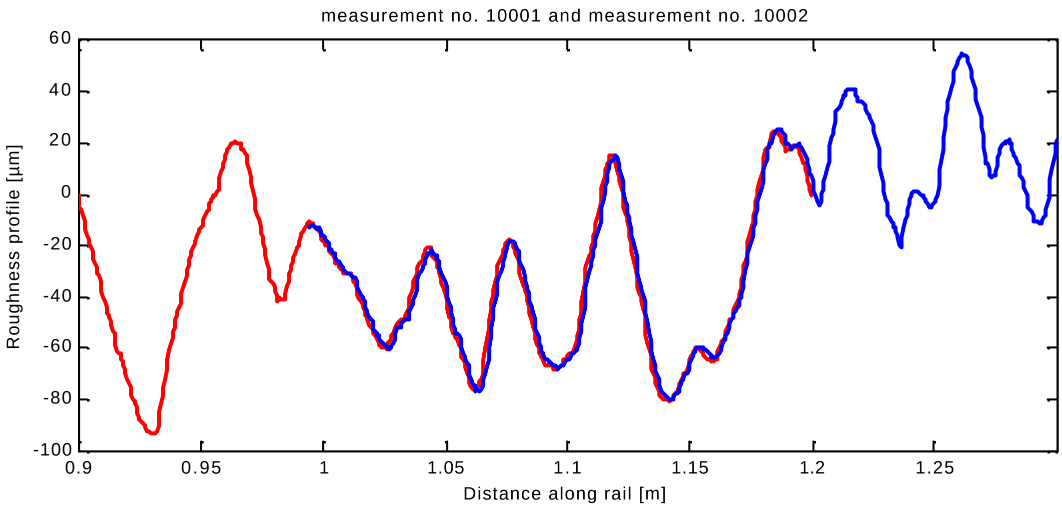


Figure 32: Result of automatic least squares fitting after manual shifting.

In cases of bad correlation, the best fit is still obtained. The eventual concatenation is done by cosine-tapering both ends and adding the lines.

It has been attempted to develop a completely automatic alignment procedure based on the cross-correlation function, but in some cases (regular corrugation patterns, or no fine structure at all) no satisfactory result were achieved. Also, cases of extreme misalignment during measurement (much more or much less overlap than 20 cm) can not be identified this way. In order to avoid these problems, the user is given full control of the procedure.

Intersubjective fitting accuracy

Intersubjective repeatability has been tested by letting two subjects do the fitting procedure for the same dataset of 4 consecutive profile lines (including the lines of Figure 30). Spectral differences for these data with good correlation were less than 0.05 dB per frequency band.

Spectral errors

Spectral errors due to concatenation have been assessed in two ways. In the first way, the successive spectra of stepwise extended concatenated profiles are examined (to be explained in the next paragraph). In the second way, the rail roughness spectrum measured by a trolley instrument is compared to that of a concatenated set of profiles.

The spectrum of the line marked '10.2 m' in 26 is calculated from 10 concatenated profiles. Also the spectra from intermediate steps, after adding one profile at the front and one profile at the back, are shown. The wavelength range grows during this process from 16 cm to 31.5 to 50 to 63 and finally to 80 cm. The spectrum of the 4.2 m data set, which yields the required 31.5 cm wavelength range, is displayed with open dots for clarity.

The spectra only deviate slightly in the common wavelength bands. These small changes are probably largely due to actual differences at the rail surface within the measurement length.

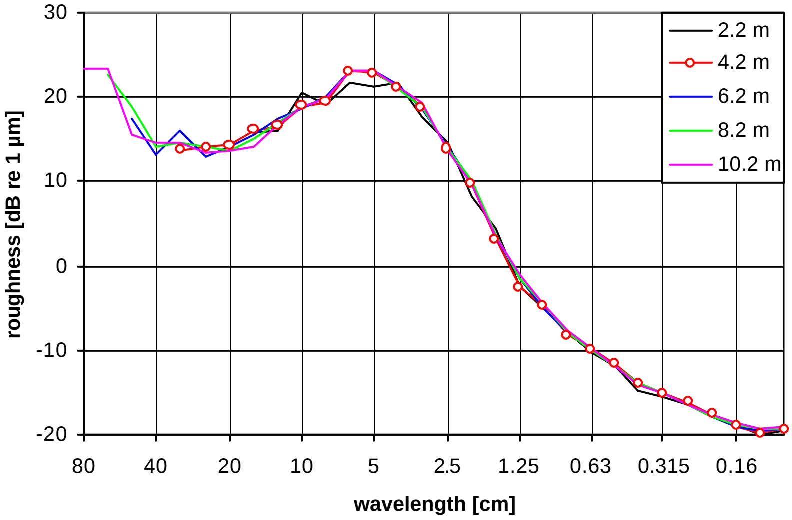


Figure 33: Roughness spectra for stepwise extending the concatenation length from 2.2 m to 10.2 m.

For the second method to uncover spectral errors, the spectra from two measurement instruments are compared (Figure 34). The first instrument is a CAT (by Loram), an accelerometer-based trolley. The second instrument is an RM1200E using the above concatenation procedure.

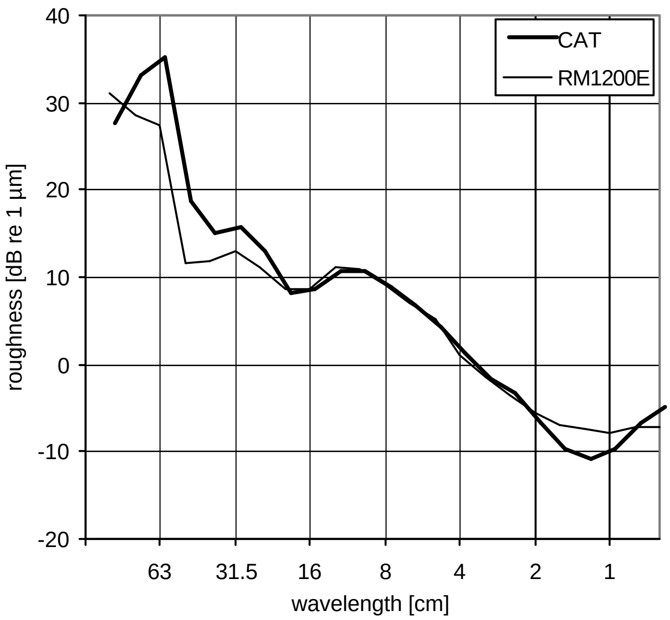


Figure 34: Comparison between spectra from two different instrument designs.

The spectra are in good agreement in the range of 2 cm to 25 cm. Outside that range, deviations up to 7 dB per octave band are found. It is not clear if the differences can be attributed to a poor concatenation routine. Also intrinsically moderate accuracy of either instrument may cause such deviations.

Influence of internal instrument misalignment

As stationary instruments like RM1200E and TRM01 partly derive their measurement accuracy from the straightness of the internal slide-bar, it is a good practice to calibrate them regularly. For example, directly after calibration, the RM1200E has a (digital) calibration horizon that deviates less than 0.5 µm from perfectly straight. After a year, deviations from perfectly straight can be of order 50 µm. Because bad calibration may lead to bad alignment of lines to be concatenated, the effect of data measured with a RM1200E with a wavy internal horizon is explored.

Figure 35 shows the effect of badly aligned data during concatenation. At first sight, these profiles do not match at all. However, by looking at the fine-structure effects (pits) near x = 2.06 and x = 2.19 m, these signals could be matched properly in horizontal direction. Clearly, concatenation is an awkward job for these signals, with possibly long wave errors in the resulting spectrum. The cumulative effect of this bad internal horizon is investigated further.

Figure 36 shows the cumulative effect of this internal error profile on concatenated data. As the shape of the internal error profile was not available (e.g. by measurement on a flat calibration stone), the error profile is estimated by averaging 60 profile lines from smooth rails measured on that same day. In this way, the local fine-structure of the profiles will cancel out, while the macroscopic waviness of the error profile remains. The resemblance between the error profile and the outer end of the red line in Figure 35 is visible.

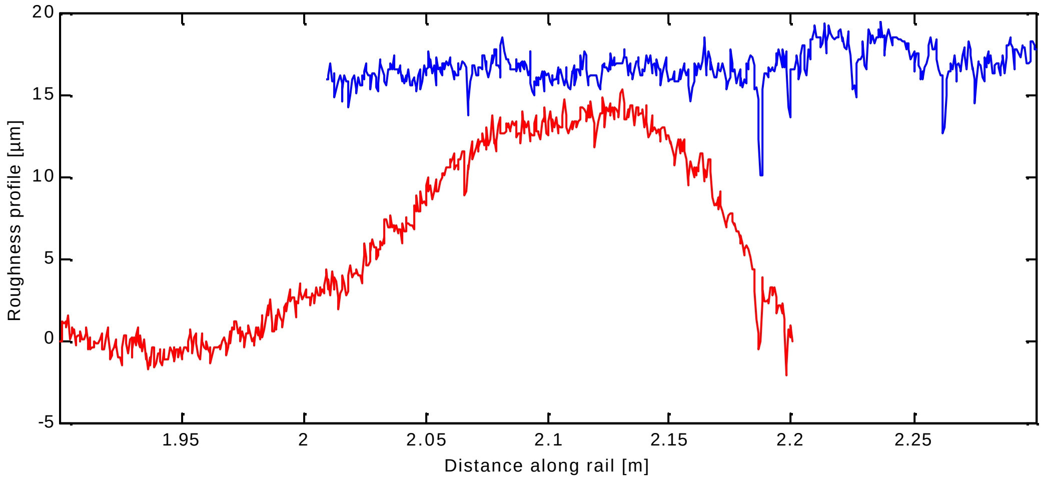
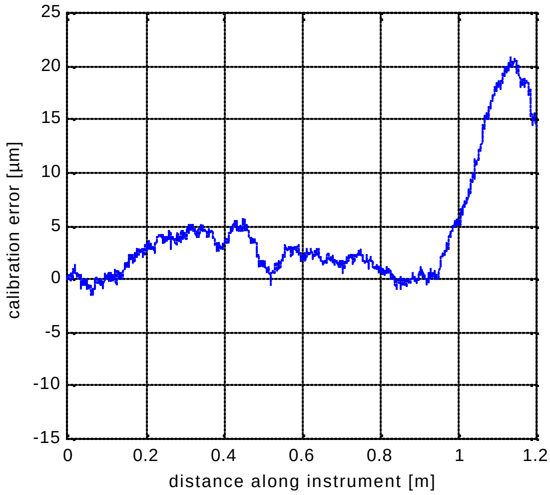


Figure 35: Badly aligned data due to uncalibrated instrument.



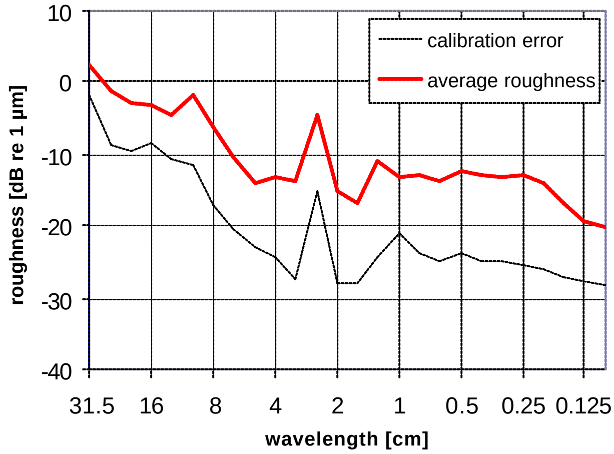


Figure 36: Left: estimated calibration error or error profile. Right: spectrum of 4 concatenated error profiles.

The right hand graph of Figure 36 shows the spectrum of 4 concatenated copies of the error profile. Also the average of 4 concatenated roughness profiles (out of these 60 lines) is shown. It appears that the error profile will not strongly contribute to the spectrum for wavelengths shorter than 10 cm, as it is about 10 dB below the average spectrum. In the range 10 cm to 31.5 cm, a contribution of 1 or 2 dB to the roughness is possible. It should be noted that the roughness of the rail considered here is quite low, which must be regarded a worst case situation. For sites with moderate roughness such error profiles will not contribute at all to the site average rail roughness.

Conclusions

It can be concluded that the concatenation procedure proposed here gives consistent results. Different numbers of concatenated profiles yield similar resulting spectra. Also, it has been shown that different users will arrive at almost the same result, which proves that the manual matching procedure is hardly subjective.

It is recommended to calibrate the instrument just before the measurements, as the roughness spectrum of smooth rails may be influenced by the internal error profile of an instrument. The influence of the error profile in such cases is 1 to 2 dB for wavelength bands longer than 10 cm.

2.2.5.6 *An efficient rail roughness procedure*

The knowledge gained in the preceding paragraphs can be combined to render a reasonably representative roughness spectrum at minimal effort with stationary 1.2 m measurement instruments:

- if one clear running band is visible, determine its width (see photograph); if the width is smaller than 30 mm, then it suffices to measure only one line on the rail under consideration;
- if the width exceeds 30 mm, or if two running bands are visible, then measure 2 (or 3) parallel lines at representative lateral positions of the rail under consideration. The position of the contact patch may become more certain if a piece of tape is stuck across the railhead before pass-by of the train of interest;
- in order to extend the spectral range, the two central sections “3” and “4” of the ISO-procedure are shifted 10 cm towards each other in order to obtain 20 cm overlap. Besides this, an additional section should be measured at either side of the two central ones, overlapping the central ones by 20 cm. Note that these additional sections are used only for long wavelength information. In cases where 2 (or 3) parallel lines should be measured, there is no need to measure these for the additional sections.
- The site average spectrum is found by averaging all measured lines energetically. This yields a spectrum up to a wavelength of 10 cm (as before with the ISO-procedure). Next, the central sections (3 | 4 | 5 | 6) are processed according to the concatenation procedure to provide additional information between 12.5 and 31.5 cm. These bands are used to extend the site average spectrum.
- For type testing purposes, all sections should be measured. Also for other purposes it is recommended that the full procedure be measured. In case of measurements on busy tracks, it is allowed to omit the outer sections 1 and 8. This procedure with only 6 sections will be called the *shorter procedure*.

An overview of this procedure is given in Figure 37. The omitted sections 1 and 8 for the shorter procedure are between parentheses.

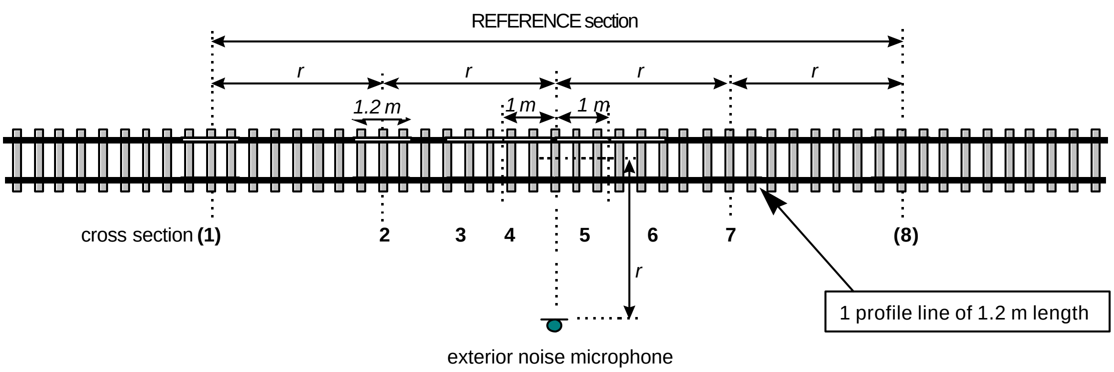


Figure 37: New proposal for rail roughness measurement procedure for instruments of 1.2 m length

In conclusion, it is mentioned here that the new proposal is based on current practice. In many cases in the Netherlands, where over 5 trains per hour pass by on most tracks, the ISO-procedure could not be maintained. This has led to improvisations made on the measurement site: sometimes parallel lines were omitted, sometimes sections were omitted. We are aware that the new proposal is not as simple and straightforward as the original ISO-procedure (version 2001), but it is an answer to the clear need to come up with a less time-consuming version.

2.2.6 Classification

2.2.6.1 Introduction

The Classification mechanism has been produced in three steps. First in an initial report, the existing data for European trains and tracks were reviewed and an initial overview was given for the possible uses of a classification system. This was presented as Deliverable 1.

Table 10 shows the preliminary classification based on the known features of vehicles, locomotives and tracks that determine the noise in broad terms.

V0	very noisy	tread braked (cast iron) and diesel
V1	noisy	rough wheels (CI block brake)
V2	quiet	smooth wheels (disc/drum/K-block)
V3	very quiet	smooth wheels and additional noise reducing measures

T0	very noise track	steel bridge without ballast
T1	noise track	bridge with ballast / track with joints / slab track without special acoustical measures
T2	standard track	ballasted track / slab track with acoustical measures
T3	very quiet track	all state of the art techniques applied on a standard track

Table 10: Preliminary Classification from Deliverable 1

An intermediate report, Deliverable 6, Part 3, gave a more thorough overview of potential instruments which could require support from a classification mechanism and presented the specifications for a classification system following from each of the applications. It was made clear in that report and it is still the case that STAIRRS does not advocate the use of these instruments but can provide supporting information about the noise characteristics of trains and tracks, if and when they are introduced.

Potential Instruments where noise classification could provide inputs were identified as listed below:

Capacity allocation.

The capacity manager might want to use acoustical properties of his infrastructure and the vehicles running on it to plan the capacity on his network. Once noise is the parameter that limits the capacity of his network, it is clear that he can run more quieter trains than noisier trains, so by classifying the trains and the infrastructure types on his network he can balance the operational space available with the noise limits being placed on him.

Access charges

An infrastructure manager that realises that he has to erect barriers for a limited number of very noisy trains on his network might want to ask the operators of these trains to pay more infrastructure access charges. Ultimately this might result in a dedicated system of noise dependent access charges. Classification of vehicles and tracks based on their noise characteristics will assist this process.

Subsidies for low noise technology

Once it is known which noise source or parameter is responsible for the greater portion of noise created, it is also possible to know where to start a noise reduction policy. A party interested in subsidising effective low noise technology can focus his financial efforts using this knowledge.

Type approval acceptance

Once infrastructure owners or capacity managers use a classification approach in allocation, access charging or for any other reason, the vehicle owner will automatically use the same approach in buying his trains. Following the same reasoning, the infrastructure owner will treat his own suppliers of track constructions in the same way.

Monitoring

As a control mechanism for some of the instruments presented above it might be necessary to check on a regular basis whether the trains and tracks still meet the requirements specified for the class they were once assigned. This is not really an application on itself, but an instrument that is needed to be able to use the other applications properly.

Using the initial and the intermediate reports, feedback from the discussions at the 3rd STAIRRS Workshop and the data in the database the basis for a classification system was defined and is presented here.

2.2.6.2 Classification Process

In Section 2.2.1 the background to separating the vehicle and track contributions (level 1 separation) and a further separation of wheel and rail roughness and the transfer functions of wheel and track (level 2 separation) were presented. It follows therefore that in order to take full account of the differences between trains and between track types, a classification system will have to consider the level of wheel and rail roughness and wheel and track transfer functions following the level 2 separation principles.

This leads to the following options.

Vehicles only: classify wheel roughness and vehicle transfer function

and

Tracks only: classify rail roughness and track transfer function

This approach seems to be the most complete and direct, but until the beginning of STAIRRS the techniques to measure these parameters independently using wayside techniques only were not available. Now that STAIRRS has developed these tools, this approach is practicable.

2.2.6.3 Classification Methodology

A three step approach is proposed:

a. Review of data. (from level 2 separation)

b. Identify (logical/natural) transition boundaries (this is the actual quantification)

c. Specify (or: name) these areas between boundaries

This approach has been followed here but it needs to be recognised that the ability to produce a definitive, wide ranging, classification system depends data being available from a variety of vehicle and track designs with a large range of noise/roughness characteristics which can be attributed to differences in designs e.g. damped wheels, damped tracks, low diameter wheels etc. Unfortunately at this stage of the development of the classification system the only data available is that obtained from the measurement campaign and separated in subsequent analysis. This does not have the variety of noise/roughness characteristics to produce a definitive classification system and it is only possible to suggest a first example as indicated in Section 2.2.6.4.

2.2.6.4 Classification, a first example

In this section the a, b and c exercise presented above will be followed for trains and tracks in the STAIRRS database.

The outcome has the following merits:

- it serves as an example, to show that classification can be done and how it is done,

- it serves to demonstrate that the harmonised data structure operates well,

- it serves to demonstrate that the measurement techniques provide usable data, that is consistent with the calculation tools and with existing data.

In summary it is a demonstration of a standard method to produce a classification of vehicles and tracks rather than a proposal for such a classification.

As a convention, in each of the cases presented below the noisiest class is defined class 0. Class 0 is then followed by two or more quieter classes, numbered 1, 2 etc. The quietest class represents a range where no trains or tracks are yet to be found. Once actual trains or tracks can be found in this 'best' class, one might consider introducing a new class, to introduce a new challenge at the same time.

Wheel Roughness

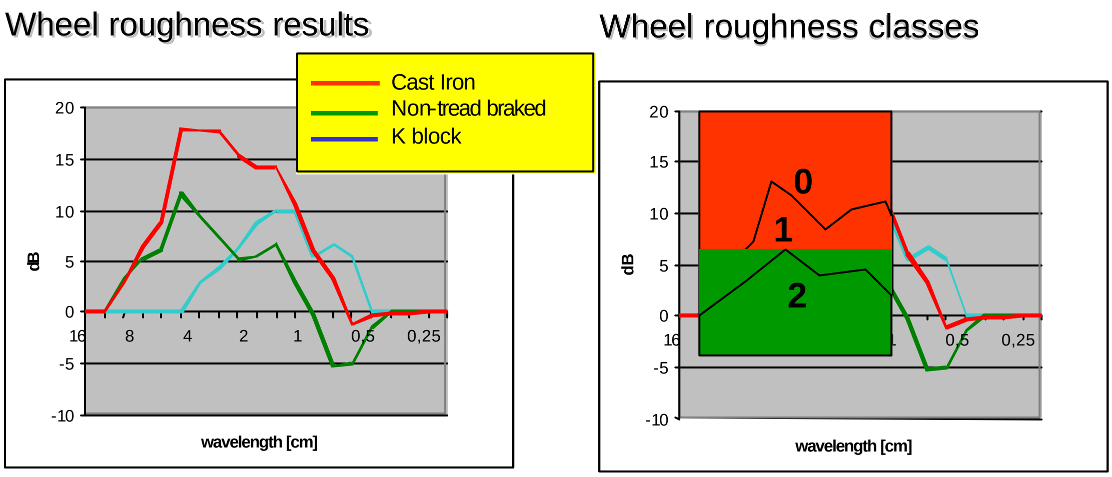


Figure 38: Example of Wheel Roughness Classification

Measurement results for wheel roughness are presented in the left hand graph above and shows the known difference in wheel roughness for different braking systems. A classification is proposed that defines a class 1 with a range of about 5 dB around the known non-tread braked wheels and the K-block tread braked wheels. This automatically defines the two remaining classes: those above this class 1 (class 0) and those below this class 1 (class 2).

Rail roughness

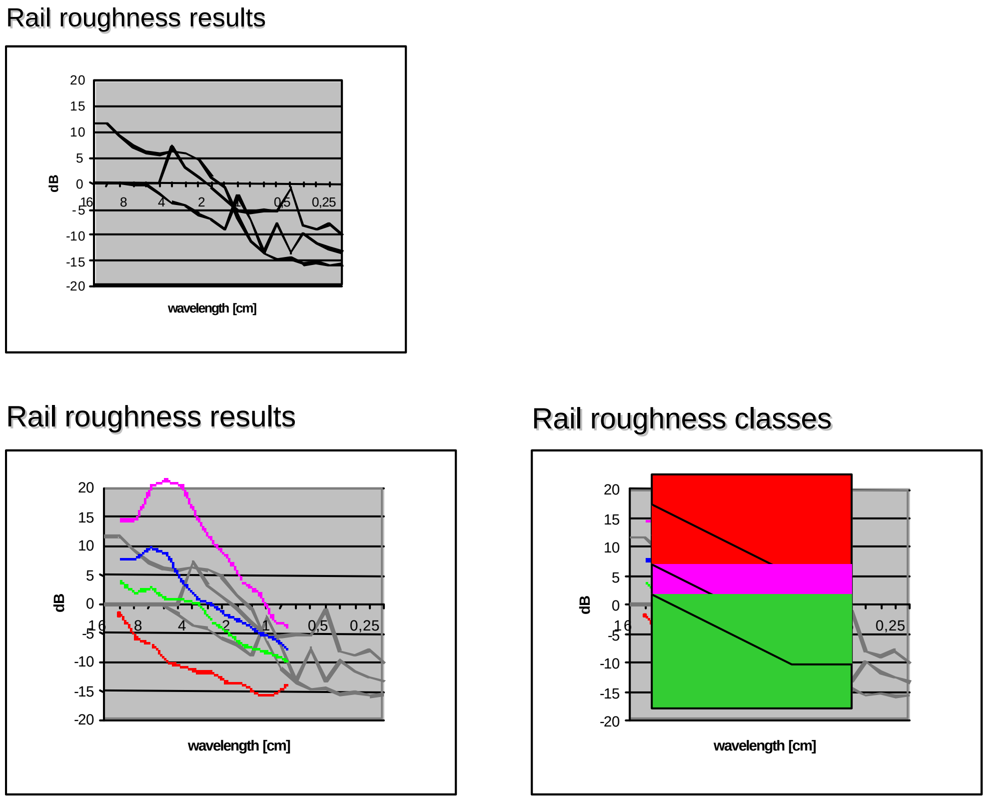


Figure 39: Example of Rail Roughness Classification

Rail roughness measurement from the STAIRRS database are shown in the top left graph. The range of data in these measurements do not show the spread that is known to exist. Additional measurements have therefore been included from previously reported sources. The pink spectrum represents heavily corrugated track, the red spectrum an extremely smooth rail. Blue and green spectra represent averagely rough rails.

These spectra have been used to propose a 5 class roughness classification, ranging from heavily corrugated (red area) to very smooth (green area).

Vehicle Transfer Function

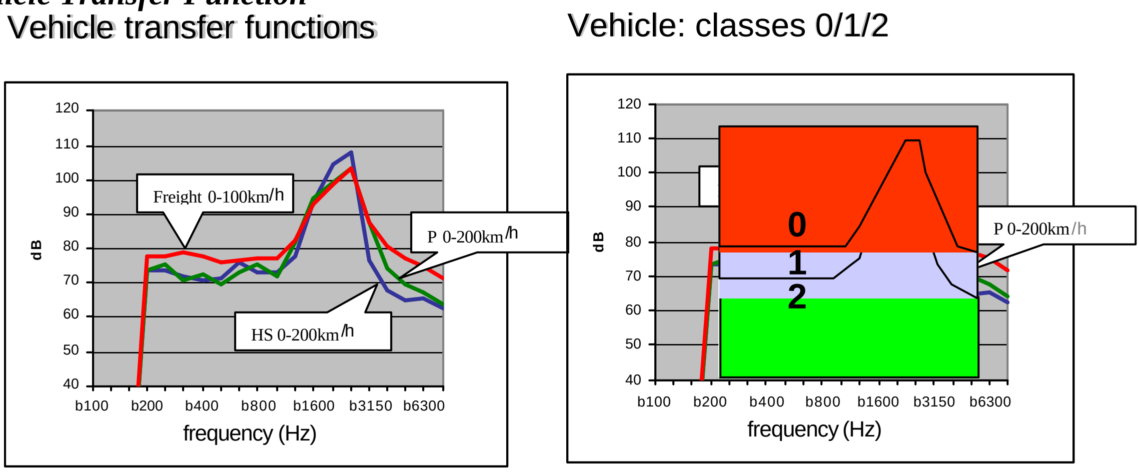


Figure 40: Example of Vehicle Transfer Function Classification

The mean spectra in the left graph show that the vehicle transfer function does not vary too much between freight, conventional passenger and high speed trains. (The vehicles measured all had wheels of very similar diameter and none were damped. This analysis caused the initial conclusion to be presented at the final Workshop that "An undamped wheel is an undamped wheel") It therefore appears that the large variations in pass-by noise normally noted between various trains on one site can be assigned to variations in wheel roughness and the axle density (number of axles per metre), and not vehicle construction parameters (other than brake system or wheel tyre quality, which determine wheel roughness). The example Classification includes these undamped wheels as Class 1, with higher radiation identified as Class 0 and lower radiation as Class 2. It is likely that Class 2 wheels will include those with damping and may also include smaller diameter wheels when reliable data has been obtained for the transfer function of such wheels.

As more data becomes available it is expected that there will be further divisions within the Class 2 area.

Track Transfer Function

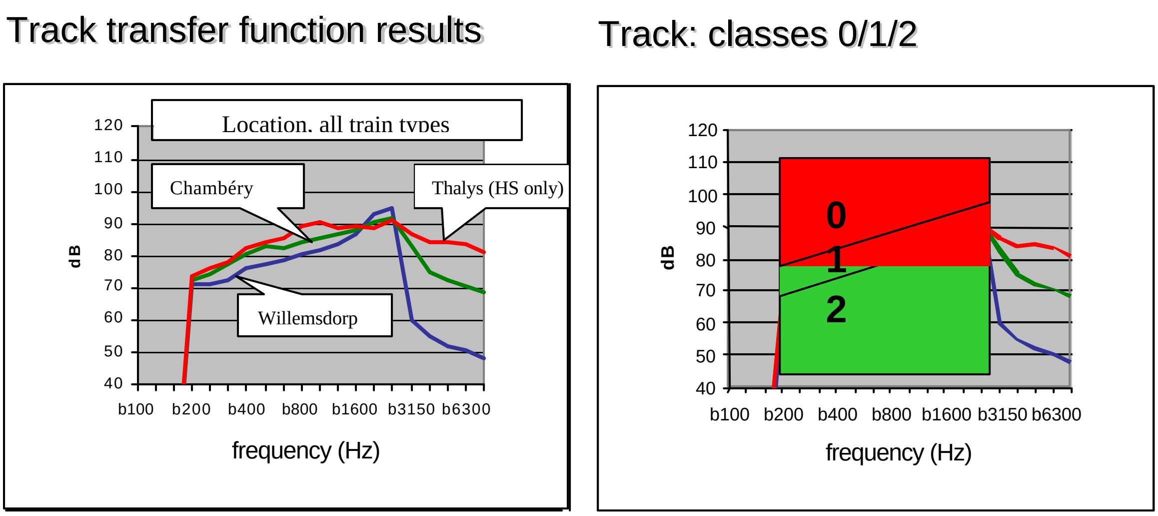


Figure 41: Example of Track Transfer Function Classification

Again there is little variation in the predicted track transfer function from separation carried out from data obtained in the STAIRRS measurement campaign. It is therefore proposed to include the means for the data in Class 1 with Classes 0 and 2 higher and lower respectively. It is expected that future data will show damped tracks in Class 2 and implemented low noise designs will allow a further subdivision of Class 2.

2.3 Work Package 3 Consensus Building Workshops

2.3.1 Introduction

Four workshops were held, attended by representatives of European and National legislative bodies, railway operators, infrastructure managers, the railway supply industry and partners in the STAIRRS project. Each is summarised below.

2.3.2 1st Workshop, Brussels, 23 March 2000

Attended by 55 delegates, the main purpose of this Workshop was to introduce the STAIRRS project to a wider audience, describe its objectives and present information on parallel work that could provide input to the project.

In addition to providing background to the project and its objectives presentations were made on recent results from Silent Freight and Silent Track projects and the UIC noise reduction programme where it is aimed to replace cast iron tread brakes on freight vehicles with brakes made of composite materials. Information from all these sources would be used in the development of the Railway Noise Strategy Support tool in WP1.

Information was also given on the, then newly formed, EU Working Group Railway Noise and it was hoped that close links could be formed between that group and the STAIRRS project.

It was concluded that the workshop had been a success although, in future, more time should be allocated for group discussion in order to attempt to reach a consensus position on a particular question. Communication was also identified as a particularly important issue which could possibly be addressed through the STAIRRS website which at that time was under development.

The STAIRRS Project Management Group in reviewing the outcome of the Workshop recognised the need for open discussion, but retained the belief that the first workshop had to "set the scene" for the future development of the project. It was felt that it had been successful in bringing together many of the influential players in railway noise activities in Europe and during breaks in the programme people from different backgrounds had taken the opportunity to talk to each other.

2.3.3 2nd Workshop, Paris, 6 & 7 March 2001

The second Workshop, held at UIC Offices, was attended by some 75 delegates, again representing European and National legislative bodies, railway operators, infrastructure managers, the railway supply industry and partners in the STAIRRS project.

During the workshop the four parties external to the project concentrated on one lead question, viz.

"What needs to be done to generate quieter railways?"

The delegates were originally split into four common interest groups ie legislators, operators, infrastructure managers and railway supply industry.

Following the results of that "brainstorm", which were communicated to the whole workshop, a number of common key issues were identified. Four different groups, each containing delegates from each of the interest groups, were convened to review the outcome of the first "brainstorm" and attempt to reach a consensus.

As a supplementary question, these mixed groups were asked to identify

"How can the STAIRRS project assist this process?"

The main conclusions of the workshop were:

- **strict legislation** is required, first for new vehicles (and track), later for existing vehicles (and track),
- this legislation needs to be **realistic,** i.e. economically achievable, based on solutions that are technically available and representative of the situation under normal practice,
- **legislative bodies** (e.g. the national governments or the European Commission) should take the first action required to establish this legislation,
- **proper timing** is essential to allow for adequate reaction from the parties involved,

HOWEVER:

- **funding** was identified as being crucial and some means had to be found to be able to transfer funding to where it was most effective, particularly if it could be shown that it was more cost effective to have source related measures on vehicles instead of barriers and façade insulation,
- others felt that **for existing freight rolling stock operators themselves** should make the first step, possibly under the regime of **voluntary agreements,**
- the option of noise control by improved **maintenance regimes** should be looked into,

It was also concluded that the STAIRRS consortium could assist in this process by:

- contributing to the funding mechanisms debate by providing **cost-benefit analyses,**
- contributing to specification and standardisation issues in the development of measurement methods, particularly by providing validated techniques for the **separation of wheel and track contribution to total rolling noise,**.

2.3.4 3rd Workshop, Paris, 5 & 6 March 2002

Again the workshop was used to present progress from the project but more importantly a Management Game had been developed which allowed groups to make decisions about noise mitigation for a number of freight, passenger and mixed lines.

Noise mitigation options included:

Infrastructure Manager options

- noise barriers
- acoustic grinding
- tuned rail absorbers
- ban noisy trains at night time
- track penalty for noisy trains
- 80 km/h speed limit

Train operator options

- replace cast iron tread brakes with K-blocks on freight vehicles

- install disc brakes on freight vehicles
- purchase low noise trains

legislative options

- subsidise new low noise trains
- introduce noise creation limits for new trains
- subsidise retrofit for existing trains

The general trend from each group, which contained a mix of representatives from infrastructure, operating and legislation was that noise control at source was preferable to the use of barriers, confirming the conclusions of the second workshop. It was interesting to note that although operating controls such as the application of speed limits were low cost options they were not used as a noise control measure since it was felt that this would be counter to the commercial competitiveness of the railway industry and was not consistent with the aim of transferring traffic from road to rail.

2.3.5 4th Workshop, 26 November 2002

At the fourth workshop the draft results of the project were presented to a group of delegates again representing the broad spectrum of the railway industry and legislators.

The broad conclusion was that the project had been successful but there was a general feeling among the delegates that progress towards the implementation of low noise railways was slow and that it was important to ensure that successful noise reduction options were developed to such an extent that they would be accepted and used in vehicle and infrastructure designs.

3 Deliverables/Milestones/Progress reports

3.1 Deliverable D1

Report STR21TR310300AEA

Classification of Rolling Stock: Initial Report

By Jan van den Brink AEA Technology Rail bv

Planned: 31/03/00

Draft issued: 31/03/00

Final issued: 12/10/00

3.2 Deliverable D2

Report NSTO/00/0130014/026

Specification data structure and software system

By Frank Elbers AEA Technology rail bv

Planned: 31/05/00

Issued: 26/06/00

3.3 Deliverable D3

Report STR12/14a171100AEA

Software System and Interface for input of national database for cost-benefit calculations

By Frank Elbers AEA Technology Rail bv

Planned: 31/08/00

Issued: 30/11/2000

3.4 Deliverable D4

Report: STR13TR010701AEA

Complete datasets for the countries A, B, CH, D, F, I, NL

By Paul van der Stap, AEA Technology Rail BV & Jakob Oertli, SBB

Planned: 30/06/01

Issued: 26/07/01

3.5 Deliverable D5

Software System for cost-benefit calculations

Deliverable D5a

Report: STR14TR300601AEA

Software System for cost-benefit calculations, Eurano 2001

By Paul van der Stap & Jan Lub AEA Technology Rail BV

Planned: 30/06/01

ß version software Issued: 19/07/01

a version software issued: 27/02/02

Deliverable D5b

Report: STR17TR070601ULB

Costs and benefit functions

By Nancy da Silva & Aude Lenders, ULB

Planned: 30/06/01

Issued: 19/07/01

3.7 Deliverable D6,

Description of database, list of tools to be developed and intermediate classification methodology

Deliverable D6, Overview report

Report: STR2TR220501AEA

Description of database, list of tools to be developed and intermediate classification methodology

By Pieter Dings, AEA Technology Rail BV

Planned: 30/06/01

Issued: 02/08/01

Deliverable D6, Part 1

Report: STR22TR110501AEA

Database Description

By Jan Lub, AEA Technology Rail BV

Planned: 30/06/01

Issued: 02/08/01

Deliverable D6, Part 2

Report: STR23TR140601TNO1

Tools to be developed for STAIRRS Work Package 2

By Michael Dittrich, TNO, Fabien Latourneaux, SNCF, Jan Lub, AEA Technology Rail BV, Philippe Pinconnat, SNCF, Marco Masoero, Politecnico di Torino & Chris Jones, ISVR

Planned: 30/06/01

Issued: 02/08/01

Deliverable D6, Part 3

Report: STR21TR300601AEA

Classification of Rolling Stock and Track: Intermediate Report

By Jan van den Brink, AEA Technology Rail BV

Planned: 30/06/01

Issued: 02/08/01

3.6 Deliverable D7

Report: STR15TR300301SNCF

Description of optimisation algorithm

By Veronique de Vulpillieres & David de Almeida, SNCF

Planned: 31/03/01

Issued: 31/05/01

3.7 Deliverable D8

Report: STR22TR010502SBB

Extrapolation Methodology

By Jakob Oertli (SBB) and Paul van der Stap (AEA Technology Rail bv)

Planned: 31/05/02

Issued: 11/06/02

3.8 Deliverable D9

Report: STR24TR311202PSIA

Noise data obtained from Measurement Campaign and STAIRRS Database

By Manfred Kalivoda (PsiA)

Planned 31/10/2002

Completed 31/12/2002

Issued 18/12/2003

3.9 Deliverable D10

Report: STR22TR111102SBB

Work Package 1 Synthesis Report

By Jakob Oertli (SBB)

Planned 31/10/2002

Issued 11/4/2003

Annex 1 Extrapolation to Individual Countries

Report: STR22TR011102SBB

By Jakob Oertli (SBB)

Planned: 31/10/2002

Issued: 11/4/2003

Annex 2 Results Eurano Calculations

Report: STR22TR310103AEA

By Paul van der Stap & Saskia Bol (AEA Technology Rail bv)

Planned: 31/10/2002

Issued: 11/4/2003

Annex 3 Short and long term approaches to the evaluation of costs and benefits

Report: STR17TR311002ULB

By Aude Lenders (ULB) & Olaf Tietje (ETH)

Planned: 31/10/2002

Issued: 11/4/2003

Annex 4 Optimisation process: tests & results

Report: STR22TR211002SNCF

By Cora Cremezi-Charlet & David de Almeida (SNCF)

Planned: 31/10/2002

Issued: 11/4/2003

3.10 Deliverable D11

Work package 2, Final Report

Part 1

Report: STR2TR261102AEA1

Umbrella report/Executive Summary

By Peter Dings (AEA Technology Rail bv)

Planned: December 2002

Issued: 18 December 2003

Part 2

Report: STR2TR261102AEA2

Final Classification Report

By Pieter Dings (AEA Technology Rail bv)

Planned: December 2002

Issued: 18 December 2003

Part 3

Report: STR23TR150702TNO1

IDR and Transfer, Theoretical Manual

By Fred de Beer, TNO

Planned: December 2002

Issued: 18 December 2003

Part 4

Report: STR23TR130902AEA1

Direct roughness measurements and Vibro-acoustic Track Noise method

By Edwin Verheijen, Peter van Tol and Marco Paviotti, (AEA Technology Rail bv)

Planned: December 2002

Issued: 18 December 2003

Part 5

Report :STR23TR261102SNCF1

MISO : A measurement method to separate noise emission of railway vehicles and tracks

By Fabien Létourneaux (SNCF - Agence d'Essai Ferroviare)

Planned: December 2002

Issued: 18 December 2003

Part 6

Report: STR23TR190902ISVR1

Transfer report, Combination of separately measured vehicle and track components of noise

By: Chris Jones, ISVR

Planned: December 2002

Issued: 3 December 2003

Part 7

Report : STR23TR130902AEA3

Measurement protocol, Excel form and vehicle label

By Edwin Verheijen, Marco Paviotti, Jan Lankelma (AEA Technology Rail bv). With contributions by Manfred Kalivoda (Psi-A)

Planned December 2002

Issued: 18 December 2003

3.11 Milestone 1

1st Consensus Workshop

Planned: March 2000

Held: 23 March 2000

3.12 Milestone 2

2nd Consensus Workshop

Planned: March 2001

Held: 6 & 7 March 2001

3.13 Milestone 3

Mid Term Review

Planned: August 2001

Held: 9 September 2001

3.14 Milestone 4

3rd Consensus Workshop

Planned: March 2002

Held: 5 & 6 March 2001

3.15 Milestone 5

4th Consensus Workshop

Planned: November 2002

Held: 26 November 2002

3.16 12 month Progress Report

Planned: February 2001

Issued: 1 June 2001

3.17 Mid Term Report

Planned: July 2001

Issued: 30 August 2001

Mid term review held: 10 October 2001

3.18 24 Month Progress Report

Planned: February 2002

Issued: 28 February 2002

3.19 36 Month Progress Report

Planned: February 2003

In preparation

3.20 Final Technical Report (Milestone 6)

Report: STR40TR181203ERRI

By Brian Hemsworth (ERRI)

Planned: February 2003

Issued: 18 December 2003

3.21 Technological Implementation Plan

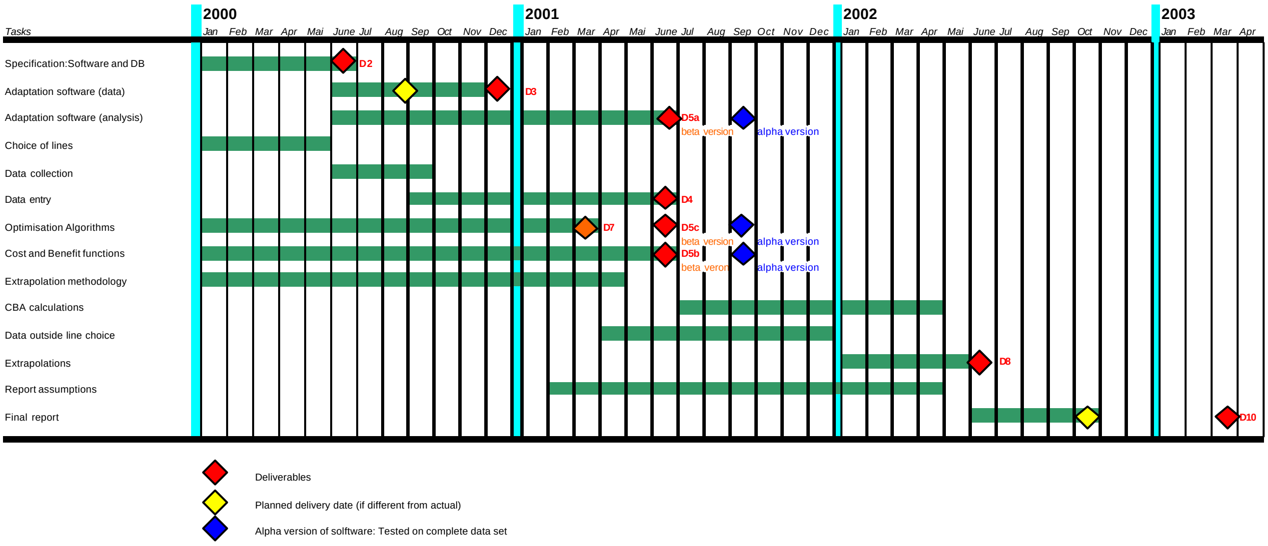
Planned: February 2003

In preparation

4 Comparison with planned activities

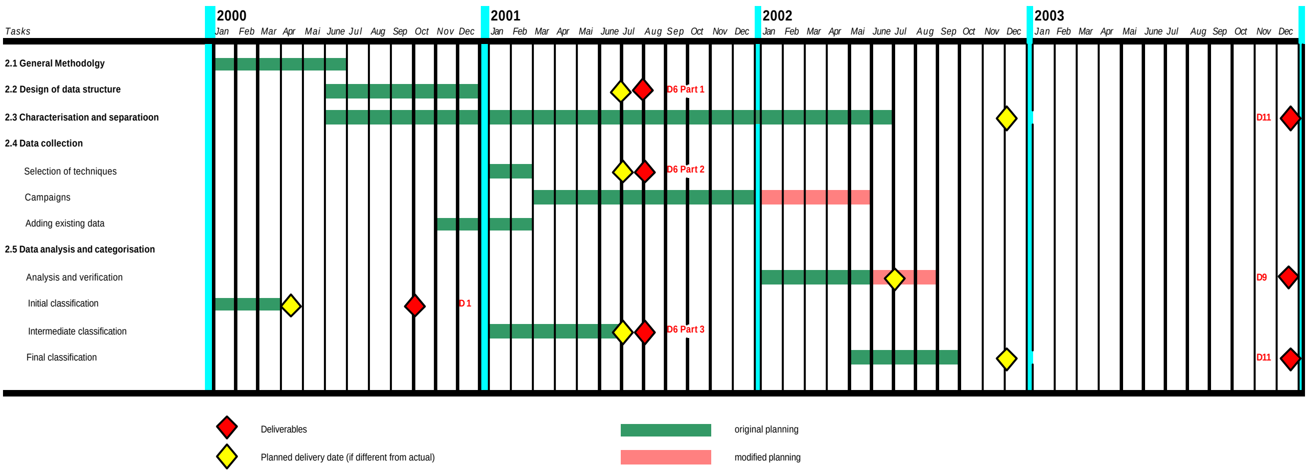
4.1 Work package 1

STAIRRS, Work Package 1
Time Schedule



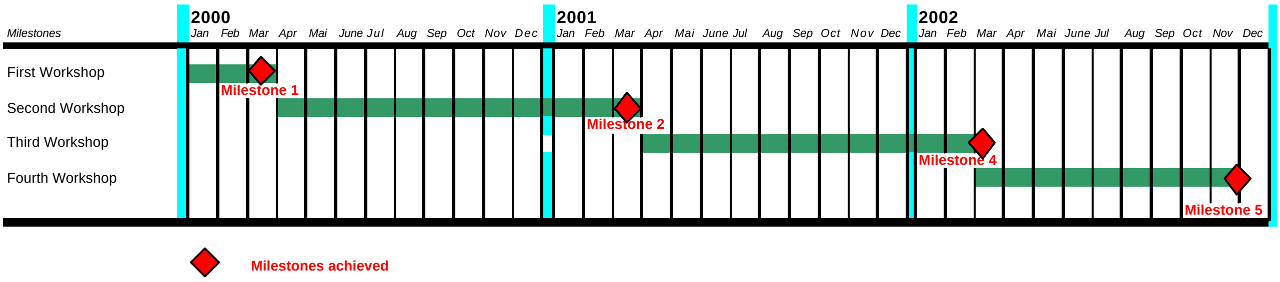
4.2 Work Package 2

STAIRRS, Work Package 2
Time Schedule



4.3 Work Package 3

STAIRRS, Work Package 3, Consensus Building Workshops
MILESTONES



5 Management and Coordination aspects

5.1 Consortium Contacts

ERRI European Rail Research Institute
Australielaan 13
3526 AB Utrecht
The Netherlands

Brian Hemsworth tel: +31 30 232 48 22
fax: +31 30 236 89 14
e-mail: bhemsworth@erri.nl

SBB SBB CFF FFS
Rail Environmental Center
Hochschulstrasse 6
CH-3000 Bern 65

Jakob Oertli tel.: +41 512 20 39 40
fax: +41 512 20 44 75
e-mail: jakob.oertli@sbb.ch

SNCF Direction de la Recherche
45 Rue de Londres
F-75379 Paris

Pierre-Etienne Gautier tel: +33 1 53 42 92 72
fax: +33 1 53 42 97 84
e-mail: pierre-etienne.gautier@sncf.fr

SNCF AEF
21 Avenue du President Allende
94407 Vitry sur Seine
Paris
France

Fabien Letourneaux tel: +33 1 4718 8232
fax: +33 1 4718 8230
e-mail: fabien.letourneaux@sncf.fr

AEA Technology Rail BV Concordiastraat 67
PO Box 8125
NL-3503 RC Utrecht
Netherlands

Pieter Dings tel: +31 30 235 70 73
fax. +31 30 235 7329
e-mail: pieter.dings@nl.aeat.com

DB AG: Bahn-Umwelt-Zentrum
Schall- und Erschütterungsschutz (TUM 5)
Deutsche Bahn AG
Schicklerstrasse 5 – 7
D-10179 Berlin

Rolf Gessner tel.: +49 30 297 63236
fax: +49 30 297 63326
e-mail: Rolf.Gessner@bahn.de

Psi-A Lastenstrasse 38/1
A-1230 Wien
Austria

Manfred Kalivoda tel. and fax: +43 1 865 67 55
e-mail: kalivoda@psia.at

TNO Stieltjesweg 1
2600 AD Delft
The Netherlands

Michael Dittrich

Tel: +31 15 269 2401
Fax: +31 15 269 2111
e-mail: dittrich@tpd.tno.nl

Politecnico di Torino Corso Duca Degli Abruzzi 24
10129 Torino
Italy

Marco Masoero tel.: +39 011 564 4441
fax: +39 011 564 4499/4503
e-mail: marco.masoero@polito.it

ETH Natural and Social Science Interface (UNS)
Swiss Federal Institute of Technology
HAD F2, ETH Zentrum
CH-8092 Zürich
Switzerland

Olaf Tietje tel.: +41 1 632 52 60
fax: +41 1 632 10 29
e-mail: tietje@uns.umnw.ethz.ch

ULB Centre d'Etudes Economiques
et Sociales de l'Environnement
Université Libre de Bruxelles
Avenue Jeanne 44
CP 124
B-1050 Bruxelles

Walter Hecq tel.: +32 2 650 33 77
fax: + 32 2 650 46 91
e-mail: whecq@ulb.ac.be

ISVR Institute of Sound and Vibration Research
University of Southampton

Highfield
Southampton SO17 1BJ
UK

Chris Jones tel: +44 2380 593224
Fax: +44 2380 593190
e-mail: cjcj@isvr.soton.ac

6 Conclusions

6.1 Work Package 1

- A tool comprising noise prediction, cost - effectiveness analysis, extrapolation and optimisation modules has been successfully developed and tested. This has allowed analysis to be carried out to compare the cost effectiveness of different noise mitigation options for the area for which detailed information is available (10 000 km of track) 21 individual countries (by extrapolation) and Europe (again by extrapolation).

  That analysis has provided the following conclusions regarding the cost effectiveness of different noise mitigation options.

- Composite brake blocks for freight rolling stock have the highest efficiency (effectiveness/cost) but provide insufficient benefit to meet potential future targets, for example the ERRAC 2020 noise reduction targets.

  In comparison with the option with the highest effectiveness smooth wheels give 38% of that effectiveness at only 5% of the cost.

  This confirms that the UIC Action Plan is the correct first step to make, both from a noise reduction point of view and on a cost basis.

- Whenever the effect of smooth wheels is combined with other mitigation the effect is increased and the cost reduced. (This is because less sound insulation and fewer barriers, when barriers are part of the mitigation, are required to achieve the target noise level of 60 dB(A) L_{den})

  This confirms that the UIC Action Plan to reduce freight train noise through smooth wheels on freight vehicles is an integral element of a future low noise railway.

- The highest benefits can be achieved with a solution combining k-blocks, optimised wheels, tuned rail absorbers, acoustic grinding and noise barriers no higher than 2 m. This solution protects almost 95 % of the population (i.e. only 5 % of the lineside population have remaining noise above an L_{den} of 60 dB(A).

  This option is 15% more effective than the option with only barriers up to 4m high and is achieved at 70% of the cost.

- Track measures in combination with rolling stock measures give a good efficiency. Combining rolling stock solutions with track measures decreases costs while remaining at the same benefits. Similarly the benefit can be increased and the costs decreased if k-blocks are added to a scenario consisting of only tuned rail absorbers.

- Noise barriers, especially if barriers up to 4 m height are allowed, have a poor cost-effectiveness. Their effectiveness, however, can be improved, if k-blocks are added. A similar increase can be expected, if track tuned rail absorbers are added, however this combination was not tested.

- Acoustic grinding by itself was predicted to have very low efficiency because, from the roughness data in the literature, even disc braked wheel roughness dominated rail roughness except in cases of high rail roughness. If wheels with k-blocks are shown to be even smoother, TWINS calculations predict a greater benefit from acoustic grinding. Specific measurements in Germany indicate a much higher noise reduction from rail grinding than predicted here. A 3 dB(A) reduction is allowed in the noise prediction model for all types of vehicles irrespective of braking system. To achieve these levels, both wheel and rail roughness must be lower than reported in the literature.[6]

- **The costs for insulated windows are very high in situations with low benefits.** Freight rolling stock solutions may have an excellent efficiency, however they are only about one third as effective as the maximum solution. Therefore, if all remaining persons with noise reception values above an L_{den} of 60 dB (A) receive insulated windows, considerable costs must be expected. These are 4 – 5 times higher than the costs for the freight rolling stock improvement itself.
- **The above conclusions hold in almost all countries.** Also, the conclusions are true both for the 11'000 km for which detailed acoustical data is available as well as for the extrapolation to 21 countries. Exceptions only occur in those countries which have an exceptionally high number of freight wagons (e.g. France) or an exceptionally low number of freight wagons (e.g. Norway). In these cases only the combination of k-blocks with optimised wheels is different, because here the costs are calculated twice.
- **Noise control is expensive**. For the 21 countries studied, the total extrapolated present costs range from € 3.5 billion (k-blocks on freight wagons) to € 76 billion (allowing a maximum of four metre barriers). These prices increase if perpetual present costs are taken into account (including price of removal after the end of the lifetime and the replacement of the measure). There the maximum costs are € 109 billion.

  However, caution must be exercised concerning the actual number persons above an L_{den} of 60 dB(A) and the actual cost of the noise mitigation options in the individual countries. All extrapolations were undertaken with average values for all of Europe, even though urban population densities vary throughout Europe. Therefore, the number of annoyed persons is overestimated in Scandinavia and underestimated in Spain or France. Additionally, the extent of urban areas was only determined in a very approximate manner. There is also a lack of comparative statistics to determine accuracy. Further work is required to obtain reliable results.

  The Final Report of Work Package 1 contains calculated costs and persons above 60 dB(A) L_{den}.. This report contains data without values to the scales to demonstrate the relative position of different mitigation options.

6.2 Work Package 2

- **Separation, characterisation and classification** of railway noise sources are essential for a successful introduction of instruments to stimulate noise reduction at the source.
- Effective measurement tools have been developed and validated to separate:
  - Wheel roughness
  - Rail roughness
  - Total roughness to wheel noise transfer function

[6] In Germany DB AG has developed a procedure called “Specially Monitored Track” (SMT) for the purpose of reducing noise generation at the source. The SMT process involves removing rail corrugations through a special grinding procedure and a periodic acoustic monitoring of the track section. Measurements show that the rolling noise reduction obtainable with the SMT process for non-corrugated wheels (disc-braked wheels or vehicles equipped with k-blocks) can be as much as 8 dB(A) but is considerably less pronounced in the case of trains with cast-iron block brakes. The Federal Railway Agency (EBA) in Germany approved –3dB(A) on an average over all kinds of trains. By making methodical use of the SMT process, around 5 million EURO per year can be saved on conventional noise control measures (e.g. noise barriers).

(wheel transfer function)

- Total roughness to track noise transfer function

  (track transfer function)

- To carry out these separation techniques a complementary set of noise and roughness measurement procedures have been developed and used in a measurement campaign for formulating a preliminary data base of separated quantities that could form the basis of a European data base. The measurement procedures will be forwarded to Standards organisations for review.
- A classification method has been proposed, and using this method, a class definition has been proposed based on the limited data contained in the preliminary database. This classification will need to be reviewed, particularly in the ranges of low noise and low roughness as more data is added to the data base and new low noise designs for vehicles and tracks are introduced.
- The measurement methods and accompanying analysis software, as well as the measurement procedure are available and the STAIRRS database is open for new data, so new class definitions can be made for new datasets fairly easy.

6.3 Work Package 3

General consensus was achieved at the four workshops with the following conclusions:

- **Noise control at source** is more effective than noise barriers
- Money should be used to implement the most cost effective noise treatment even if this means reviewing funding regulations within the European Community
- The major impetus for lower noise levels in the future would come from **strict noise creation legislation** for new vehicles and track. This may later be applied to existing vehicles and track.

  This legislation should be realistic and economically achievable.
- Noise mitigation by applying operational constraints (eg speed restrictions) was not compatible with the commercial competitiveness of railways, especially when the Commission’s policy is to transfer traffic from road to rail.
- STAIRRS can assist the development of future low noise railways by providing tools for cost-benefit analysis (WP1) to support the funding debate and by providing validated techniques for the separation of the wheel and track contribution to total rolling noise (WP2).

7 Bibliography

Work Package 1

1. J. Oertli and D. Wassmer, Rail Noise Control in Switzerland: Legislation, Environment, Politics and Finances, Journal of Sound and Vibration 193, 403-406, 1996
2. J. Oertli, Cost-Benefit Analysis in Railway Noise Control. Journal of Sound and Vibration, 231, 505-509, 2000.
3. J. Oertli, European Rail Noise Abatement, Internoise Nice, France 2000.
4. J. Oertli, F. Elbers, M. Beier, S. Joncour, B. Hemsworth, Cost-Benefit Analysis final report, UIC Task Force Noise, 1999.
5. F:B.J. Elbers, Consequences of noise creation quotas for railways in the Netherlands, NS Technish Onderzoek, 1998
6. L. de Boer and A. van Beek, Low noise trains in broad perspective KPMG and NS Technisch Onderzoek, 1999
7. H. Miedema, Response functions for environmental noise in residential areas, TNO report (92.021), September 1992
8. B Hemsworth (ERRI) and RRK Jones (AEA Technology rail Ltd), Silent Freight: Development of New Technologies for Low Noise Freight Wagons, 4th Framework Programme of the EU. Final report 5E0U15T1.DB December 2000
9. J. de Villers, J.-M. Reniers, W. Hecq: "Building of one set of sustainable development indicators for transportation in Belgium". Study carried out for the Federal Office for Scientific, Technical and Cultural Affairs. Project of Scientific support for a sustainable development. Partie I - 108 p., partie II -336 p. + annexes. 2000.
10. V. Favrel, W. Hecq: "External costs of air pollution generated by road traffic in the Brussels urban area" in International Journal of Vehicle Design. Vol. 27, Nos. 1-4, - pp. 129-139. 2001
11. V. Favrel, T. Pons, K. Marechal, C. Ferdinand, P. Claeys, W. Hecq: "Sustainable Mobility in Brussels - Analysis of the impacts on the environment - Evaluation of environmental externalities". Research carried out for the Federal Office for Scientific, Technical and Cultural Affairs. Programme of scientific support for a sustainable development. 68p. + annexes 300p. 2001.
12. W. Hecq in "Guidelines for defining and documenting data on costs of possible environmental protection measures"'. Technical report n° 27. European Environmental Agency. Copenhagen, 1999.
13. V. Landrain, N. Da Silva, V. Favrel, W. Hecq: "Electric and hybrid vehicles - a measure to reduce tropospheric ozone ? A cost-benefit analysis". Research carried out for the Federal Office for Scientific, Technical and Cultural Affairs. Programme of scientific support for global change and sustainable development. 97 p. + annexes 2001.
14. V. Landrain, Y. Delmotte, W. Hecq: “Stranded costs of atmospheric pollutant control equipment under the deregulation of the electricity market”. Final report for the Ministry of Economic Affairs. 90p + annexes.1998.

15. S. Meyer, W. Hecq: " Assessment of the development of micro-cogeneration: energy, environmental and socio-economic impacts". Study carried out for the Walloon Region, Intermediary Report, 72 p. 2002.

16. P. Safonov, V. Favrel and W. Hecq, "Environmental Impacts of Mobility and Urban Development: A Case Study of the Brussels-Capital Region". in "Managing for Healthy Ecosystems" Chapter 73, pp 735-750 - CRC Press 2002 (To be published)

17. J. Van Mierlo, V. Favrel, S. Meyer, L. Vereecken, G. Maggetto and W. Hecq, "How to define clean vehicles? Environmental Impact Rating of Vehicles" Proceedings of the 15th Electric Vehicle Symposium: "A future for the City" - Monaco, France, March 2002.

18. F B J Elbers, STAIRRS Deliverable D2, Report NSTO/00/0130014/026, “Specification data structure and software system”, AEA Technology rail bv, June 2000

19. F B J Elbers, STAIRRS Deliverable D3, Report STR12/14a171100AEA “Software system and Interface for input of national database for cost-benefit calculations”, AEA GTechnology rail bv, November 2000

20. Paul van der Stap, STAIRRS Deliverable D4, Report STR13TR010701AEA, “Complete data set for the countries A, B, CH, D, F, I, NL” AEA Technology rail bv, July 2001.

21. Paul van der Stap and Jan Lub, STAIRRS Deliverable D4, Report STR14TR300601AEA, “Software System for cost-benefit calculations, Eurano 2001” AEA Technology rail bv, July 2001.

22. Nancy da Silva and Aude Lenders, STAIRRS Deliverable D5b, Report STR17TR070601ULB, “Costs and benefits functions”, ULB, September 2001.

23. Veronique de Vulpillieres and Davis de Almeida, STAIRRS Deliverable D7, Report STR15TR300301SNCF, “Description of optimisation algorithm”, SNCF, May 2001

24. Jakob Oertli and Paul van der Stap, STAIRRS Deliverable D8, Report STR22TR010502SBB, “Extrapolation Methodology”, June 2002

25. Jakob Oertli, STAIRRS Deliverable D10 Report: STR22TR111102SBB “Work Package 1 Synthesis Report”, March 2003

26. Jakob Oertli, STAIRRS Deliverable D10 Annex 1, Report STR22TR011102SBB “Extrapolation to Individual Countries”, SBB, March 2003

27. Paul van der Stap & Saskia Bol, STAIRRS Deliverable D10 Annex 2, Report STR22TR310103AEA, “Results Eurano Calculations”, AEA Technology Rail bv, March 2003

28. Aude Lenders (ULB) & Olaf Tietje (ETH), STAIRRS Deliverable D10 Annex 3, Report STR17TR311002ULB, “Short and long term approaches to the evaluation of costs and benefits”, March 2003

29. Cora Cremezi-Charlet & David de Almeida, STAIRRS Deliverable D10 Annex 4, Report STR22TR211002SNCF “Optimisation process: tests & results” SNCF, March 2003

30. Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise, Official Journal of the European Communities L189, 18 July 2002

31. Brian Hemsworth, Silent Track: Development of New Technologies for Low Noise Tracks, 4th Framework Programme of the EU. Final report 00615/7/ERRI/T/A December 2000

32. TWINS: Track Wheel Interaction Noise Software. cf: www.erri.nl/portfolio/software/twins/twins.html

33. B Berglund, L Lindvall & D H Schwela (Eds) "Guidelines for Community Noise" World Health Organisation, 1999

34. R J Brent , "Applied Cost - benefit Analysis" 1999

35. A P Bradley "Cost-effectiveness analysis: an assessment of its application in humanitarian assistance", Asia Pacific Press, 1999

36. FS-Trenitalia, SBB and DB AG, "Refitting Scenarios for noise reduction: UIC Action Programme noise reduction freight traffic", 2001

37. P Hofstetter, "Perspectives of life cycle impact assessment: A structured approach to combine models of the technosphere, ecosphere and va luesphere" Boston, Kluwer Academic Publishers, 1998

38. INGRAS "External Costs of Transport - Accident, Environmental and Congestion Costs of Transport in Western Europe" UIC, 2000

39. C Loderer, P Jorg, K Pichler & P Zgraggen, "Evaluation Handbook: Practical Methods and models for the evaluation of projects, enterprises and strategies" Zurich, 2000

40. I Marlowe, K King, R Boyd, R Bouscaren, J Pacyna & P Bosch "Guidelines for defining and documenting data on costs of possible environmental protection measures" Technical Report 27, European Environmental Agency, 1999

41. H Miedama and C Oudshoorn, "Annoyance from Transportation noise: Relationships with exposure metrics DNL and DENL and their confidence intervals", Environmental Health 109 (4), 2001

Work Package 2

42. Fred de Beer, Jan Verheij, 'Experimental Determination of Pass-by Noise Contributions from the Bogies and Superstructre of a Freight Wagon', Journal of Sound and Vibration, volume 231(3), pp.639-652, 2000

43. Fred de Beer; D11/Part 3, IDR and Transfer, Theoretical Manual, TNO, STAIRRS Level 2 Measurement Methods: Indirect roughness and transfer function, STR23TR150702TNO1.doc

44. Jan van den Brink; Deliverable 1: Classification of Rolling Stock and Track / Initial report, STR21TR310300AEA, September 2000

45. Jan van den Brink; Deliverable 6, part 3: Classification of rolling stock and track, Intermediate report, STR21TR310300AEA, July 2001

46. Pieter Dings; D6 Part 1, Umbrella report, AEAT, STR2TR220501AEA.doc, May 2001

47. Pieter Dings; D11/Part 1: Umbrella report/Executive Summary, STR2TR261102AEA1.doc, November 2003
48. Pieter Dings; D11/Part 2, Classification, STR2TR261102AEA2.doc, November 2003
49. Michael Dittrich, C.J.C. Jones, J. Lub, P. Pinconnat : 'Survey of measurement methods for railway noise', STAIRRS report no. STR21TR280400TNO, March 2001
50. Michael Dittrich, Chris Jones, Jan Lub, Philippe Pinconnat; Deliverable 6, part 2: Survey of measurement methods for railway noise and proposed developments in STAIRRS WP2, STR23TR140601TNO1, June 2001
51. Michael Dittrich, Pollone G., Kalivoda M., Lub J., Pinconnat P., Hanreich W., 'Results of the METARAIL Round Robin Test for Rolling noise', Proceedings International Congress on Sound and Vibration, Copenhagen, July 1999
52. Michael Dittrich, Janssens M.H.A., 'Improved Measurement Methods for Railway Rolling Noise', Journal of Sound and Vibration, volume 231(3), pp.595-609, 2000
53. Michael Dittrich, J. Lub, G.Pollone, M. Kalivoda: 'Methodologies for Type Testing and Monitoring of Railway Noise (Task III.4)', METARAIL report D10, TNO, August 1998
54. Michael Dittrich, M.H.A. Janssens, T.C van den Dool, W.J. van Vliet, G. Pollone, M. Kalivoda, M. Kudrna, J. Lub, P. Pinconnat, W. Hanreich: 'Application of Type Testing Methodologies - Round Robin Test and Low Noise Solutions', METARAIL report D11, TNO, February 1999
55. Anders Frid, "A quick and practical experimental method for separating wheel and track contributions to rolling noise", Journal of Sound and Vibration **231** (3), 2000
56. Chris Jones and D.J. Thompson, Combination of separately measured vehicle and track components of noise, October 2002. STAIRRS report reference STR23TR190802ISVR1.doc
57. Chris Jones, A.D. Monk-Steel and D.J. Thompson, TWINS predictions of vehicle and track transfer functions relating to the Caen measurement campaign, June 2002. STAIRRS report reference STR25TR240602ISVR1.doc
58. Chris Jones and Thompson DJ, Level 3 of the vehicle and track noise database: modelling, ISVR Contract Report No. 00/33, STAIRRS report ref. STR21TR210700ISVR1. November 2000
59. Chris Jones;D11/Part 6, Transfer report, ISVR, , STR23TR190902ISVR1.doc
60. Fabien Letourneaux; D11/Part 5, MISO, SNCF, STR23TR261102SNCF1.doc
61. Jan Lub; Deliverable 6, part 1: Database description, STR22TR110501AEA, July 2001
62. Marco Masoero, A. Mello, F. Molinari : 'Application of advanced signal processing techniques to railway noise and vibration', STAIRRS report no. STR23TR150601Poli1, 22 May 2001
63. David Thompson, Janssens M.H.A., 'TWINS Theoretical Manual version 2.4', TNO report TPD-HAG-RPT-93-0124, Delft, December 1996 (revised).

64. David Thompson and C.J.C. Jones, Study of the sensitivity of the indirect roughness method to variations in track and wheel parameters. June 2001. STAIRRS report reference STR23TR030501ISVR1
65. David Thompson and C.J.C. Jones, The assessment of various vehicles for possible use as a quiet vehicle in order to measure track noise, June 2001. STAIRRS report reference STR23TR300401ISVR1
66. A.D. Monk-Steel, D.J. Thompson and C.J.C. Jones, Theoretical study of variability of noise due to parameter variability, June 2002. STAIRRS report reference STR23TR240602ISVR2.doc
67. Edwin Verheijen; 'Results of the benchmark on roughness measurements and analysis', Proceedings of the Workshop Roughness Measurements, Utrecht, The Netherlands, 31 May 1999.
68. Edwin Verheijen; D11/Part 4, VTN / Direct Roughness , AEAT, STR23TR130902AEA1.doc
69. Edwin Verheijen and Marco Paviotti; D11/Part 7, Measurement protocol, AEAT, STR23TR130902AEA3.doc

Work Package 3

1. Paul de Vos, STAIRRS Report STR3TR060901AEAT, “Synthesis and Conclusions of the Second Consensu Building Workshop 6 & 7 March 2001, Paris” AEA Technology rail bv, September 2001.

8 Conference Papers

Internoise 2001, den Haag, August 2001

The STAIRRS Project: A cost-benefit analysis of different measures to reduce railway noise on a European scale

By J. Oertli (Swiss Federal Railways), P van der Stap and F. Elbers (AEAT Rail BV)

An optimisation process for improving cost benefit analysis software tools

by Sylvie Guerrand and David De Almeida (SNCF)

Cost-Benefit Analysis of Rail-Noise Reduction

By Nancy da Silva, Aude Lenders (CEESE, ULB, Bruxelles) and Thomas Baumgartner, (UNS, ETH Center Zurich)

Noise classification of rolling stock and track.

By Jan Lub, Jan van den Brink, (AEA Technology Rail BV)

Measurement procedures for determining railway noise emission as input to calculation schemes

By Michael Dittrich and Marcel Janssens (TNO)

17th International Congress on Acoustics ICA 2001, Rome September 2001

The STAIRRS Project

By Marco Masoero, Politecnico di Torino

7th International Railway Noise Workshop,2001, Portland, Maine, October 2001

The STAIRRS Project, Work Package 1: A cost-benefit analysis of railway noise reduction on a European scale

By Jakob Oertli**,** Swiss Federal Railways,

Separation, characterisation and classification of railway noise sources

By Pieter Dings, AEA Technology Rail BV

How the Money Machine may help to Reduce Railway Noise in Europe

By Paul de Vos, AEA Technology Rail BV

NoiseCon 2001, Portland Maine, October 2001

Railway Noise Legislation: A European Perspective

By Brian Hemsworth, ERRI

This included a description of the STAIRRS project, its work packages and how it fits into the railway noise legislative scheme in Europe.

Developments in the modelling of wheel-rail rolling noise

By**.** Chris Jones, David Thompson and Tienxing Wu, ISVR

Institute of Acoustics Spring Conference, Salford, March 2002

A study of the use of vehicles with small wheels for determining the component of noise from the track.

By David Thompson and Chris Jones, ISVR

Inter - Noise 2002, Dearborn, Michegan, USA, August 2002

The cost and benefit functions in the STAIRRS project: Strategies and Tools to Assess and Implement noise Reducing measures for Railway Systems. »

Aude Lenders and Walter Hecq W, 2002., ULB

Forum Acusticum, Sevilla, 2002

Environmental Railway Noise: a source separation measurement method for noise emissions of vehicles and track

By F Letourneaux, O Coste, C Mellet and P Fodiman, SNCF AEF

Rail-Tech Europe 2003, Utrecht, April 2003

5th Framework EU project: Stategies and Tools to Assess and Implement noise Reducing Measures for Railway Systems (STAIRRS)

by Brian Hemsworth (ERRI)

Acoustical Characterisation of rail vehicles and tracks

By Michael Dittrich et al, TNO

European Conference on Noise Control, EURONOISE 2003, Naples, May 2003

Characterisation and Classification of railway noise sources

By Pieter Dings, AEA Technology Rail bv

Responsibility attribution of railway noise: vehicle or track

By Marco Paviotto and Edwin Verheijen, AEA Technology Rail bv

The STAIRRS project work package 2: A cost - effectiveness analysis of railway noise reduction on a European Scale.

By Jakob Oertli, SBB

Noise Type Testing of a freight wagon according to the STAIRRS measurement protocol

By Manfred Kalivoda, Psi-A Consult

An advanced model for the use in the prediction of wheel-rail rolling noise

By Chris Jones, David Thompson and Tienxing Wu, ISVR

World Congress on Railway Research, 2003, Edinburgh, October 2003

STAIRRS - Stategies and Tools to Assess and Implement noise Reducing Measures for Railway Systems

By Brian Hemsworth, ERRI

MISO: A measurement method to separate noise emission of railway vehicles and tracks

By Fabien Letourneaux, SNCF

VTN: a validated method to separate track and vehicle noise and to assess noise reduction measures

By Edwin Verheijen, AEA Technology rail bv

EC Workshop: Railway Noise Abatement in Europe, Brussels, 29 October 2003

The Strategic Results of the STAIRRS project

By Brian Hemsworth, ERRI