DELIVERABLE D1.4

Part II Linking detailed mitigation studies to global noise maps

CONTRACT N° TIP4-CT-2005-516420
PROJECT N° FP6-516420
ACRONYM QCITY
TITLE Quiet City Transport
Subproject 1 Noise mapping & modelling - Identification of hot-spots
Work Package 1.2 Noise maps after integrating action plan measures
Evaluation of measures due to noise annoyance, noise levels and possibilities of realisation
Written by Geert Desanghere AKR
Date of issue of this report January 30, 2009

PROJECT CO-ORDINATOR	Acoustic Control	ACL	SE
PARTNERS	Accon	ACC	DE
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	University of Thessaly	UTH	GR
	Voestalpine Schienen	VAS	AT
	Zbloc Norden	ZBN	SE
	Union of European Railway Industries	UNIFE	BE

PROJECT START DATE February 1, 2005
DURATION 48 months

Project funded by the European Community under the SIXTH FRAMEWORK PROGRAMME
PRIORITY 6
Sustainable development, global change & ecosystems

This deliverable has been quality checked and approved by QCITY Coordinator
Nils-Åke Nilsson

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0 EXECUTIVE SUMMARY

0.1 OBJECTIVE OF THE DELIVERABLE

Linking outcomes of elaborated mitigation studies in which dedicated specific noise calculation tools are used, to the global noise maps. Important is that significant improvements due to mitigation measures are not "lost" because of the approach used in global noise mapping.

0.2 STRATEGY USED AND/OR A DESCRIPTION OF THE METHODS (TECHNIQUES) USED WITH THE JUSTIFICATION THEREOF

Check of mitigation method can be distributed/modelled with available elements in existing models for strategic noise mapping.
If not, check if this will/would be handled/modelled more accurately in other existing or future global models.
If not, propose another approach.

0.3 BACKGROUND INFO AVAILABLE AND THE INNOVATIVE ELEMENTS WHICH WERE DEVELOPED

Recall: list of possible mitigation measures out of D6.2.

0.4 PROBLEMS ENCOUNTERED

None.

0.5 PARTNERS INVOLVED AND THEIR CONTRIBUTION

AKR:	§2 – Rail transport
ACL:	§3 – Road transport

0.6 CONCLUSIONS

It can be concluded that the actual calculation methods are mostly not designed to take this kind of mitigation measures into account.
Some of the mitigation measures, although not foreseen or defined in the actual computation method could anyhow be included in the actual calculation methods.
But in general, future calculation methods, being described as 1/3 octave spectral transfer function calculation, yield all the flexibility to add 1/3 spectral correction functions, apt to include all types of mitigation measures.

0.7 RELATION WITH THE OTHER DELIVERABLES (INPUT/OUTPUT/TIMING)

Provides additional information for WP6.2 Action Plans.
Provides methods for calculation Updated Noise Maps, according to the renewed Action Plans.

1 INTRODUCTION

1.1 METHODOLOGY

An extensive list of mitigation measures has been established in deliverable D6.2 for different kind of sources (road, rail) as well as propagation paths and receivers.

The aim of WP1.2.2 is the evaluation of the possibility to integrate mitigation measures into noise maps and consequently other evaluation parameters (number of people annoyed, ...). Some mitigation measures can be integrated directly into noise maps because the considered items (such as road surface, vehicle speed, ...) are specific input variables in the noise calculation methods.

Other parameters (such as rail quality, rail lubrication, traffic flow fluidity, specially shaped barriers, ...) are not specific input variables and need an indirect input. The possibility to integrate those parameters in actual (and future) calculation aspects is studied hereafter.

Further, the aspect of loosing the effect of smaller and local mitigation measures into a global noise map is studied in further detail.

Following approach is used hereafter:

- the list of possible mitigation measures of D6.2 is used as a starting point;
- each mitigation (or group of mitigation) measure then is studied;
- first, the models used to study the mitigation measure in detailed are summarized;
- second, the way this mitigation measure has to be integrated in actual noise maps is given, taking into account recommendations of the WG-AEN "*Guide of good practice*";
- then, eventual improvements in modelling foreseen in future calculation models (cfr. HARMONOISE, IMAGINE, ...) are studied;
- final conclusion and recommendations are made.

2 RAIL TRANSPORT

2.1 INTRODUCTION

The various categories of wheel/rail noise include:

1. continuous noise source - rolling noise at tangent track:
   - normal rolling noise,
   - excessive rolling noise,
   - impact noise, and
   - corrugated rail noise.
2. local noise sources:
   - curving noise,
   - special trackwork noise;
   - open deck steel bridges.

In each of these categories, mitigation measures are proposed for bogies (wheels) and trackwork (D6.2).

2.1.1 Normal Rolling Noise

ref. GM-RAIL-	location	action	noise reduction [dB(A)]
GM-RAIL-1	vehicle	resilient wheels	1 to 2
GM-RAIL-2	trackwork	trackbed absorption	5
GM-RAIL-3		tuned rail vibration absorbers	1 to 3
GM-RAIL-4		global rail dampers	2 to 3
GM-RAIL-5		global rail dampers & wheel dampers	5 to 7
GM-RAIL-6		embedded rail with absorbent trackbed	1 to 3
GM-RAIL-7		new rail type with/without adapted pad stiffness	2 to 5
GM-RAIL-8		special rail profiles	5

2.1.2 Excessive Rolling Noise

ref. GM-RAIL-	location	action	noise reduction [dB(A)]
GM-RAIL-8	vehicle	wheel truing	7 to 10
GM-RAIL-9	trackwork	rail grinding	7 to 10

2.1.3 Impact Noise

ref. GM-RAIL-	location	action	noise reduction [dB(A)]
GM-RAIL-8	vehicle	wheel truing	7 to 10
GM-RAIL-10		slip-side control	7 to 10
GM-RAIL-9	trackwork	rail grinding	7 to 10
GM-RAIL-11		defect welding & grinding	0 to 3
GM-RAIL-12		joint maintenance	2 to 3
GM-RAIL-13		field welding of joints	5
GM-RAIL-14		eliminate rail support looseness	5

2.1.4 Corrugated Rail Noise

ref. GM-RAIL-	location	action	noise reduction [dB(A)]
GM-RAIL-8	vehicle	wheel truing	7 to 10
GM-RAIL-15		friction modifier	NA
GM-RAIL-8		wheel profile and diameter tolerance	-
GM-RAIL-9	trackwork	aggressive rail grinding	7 to 10
GM-RAIL-16		reduced rail support stiffness	-
GM-RAIL-17		head hardened rail	-

2.1.5 Curving Noise Control

ref. LC-	location	action	noise reduction [dB(A)]
LC-RAIL-1	vehicle	resilient wheels	10 to 20
		other wheel dampers:	
LC-RAIL-2		▪ constrained layer damped wheels	5 to 15
LC-RAIL-3		▪ ring damped wheels	5 to 10
LC-RAIL-4		▪ wheel vibration absorbers	5 to 15
		large radius effects:	
		▪ steerable bogies	elimination at large radius curves
		▪ onboard friction modifier	possible elimination
LC-RAIL-5	trackwork	flange lubrication	partially eliminates squeal
LC-RAIL-6		water spray lubrication	eliminates squeal
LC-RAIL-7		laterally resilient rail fasteners	15 to 30
LC-RAIL-8		top of rail friction modifiers/lubricants	reduces squeal

2.1.6 Special Trackwork

ref. LC-	location	action	noise reduction [dB(A)]
LC-RAIL-9	vehicle	resilient wheels	3
LC-RAIL-10	trackwork	moveable point frogs	7 to 10
LC-RAIL-11		spring frogs	3
LC-RAIL-12		embedded turnouts without discrete fixation	7 to 10
GM-RAIL-9	trackwork	rail grinding	7 to 10
GM-RAIL-11		defect welding & grinding	0 to 3
GM-RAIL-12		joint maintenance	2 to 3
GM-RAIL-13		field welding of joints	5
GM-RAIL-14		eliminate rail support looseness	5

2.1.7 Steel bridges

ref. LC-	location	action	noise reduction [dB(A)]
LC-RAIL-13	trackwork	moving special trackwork away from bridges	10
LC-RAIL-14	bridge	vibration isolation of rail	6
LC-RAIL-15		bridge vibration damper	2 to 4
LC-RAIL-16		plate damping	2 to 4

2.2 WHEEL/RAIL CONTACT NOISE

2.2.1 Introduction

In urban track (and track in general), noise generated by the wheel/rail contact is the dominant source in tangent track.

Therefor, lots of measurements and acoustical models have been derived to accurately predict noise.

Sensitivity analysis carried out for tram and metro network indicated that wheel and rail roughness is the most important parameter to reduce noise emission at a given speed.

Reductions up to 15 dB were indicated by both theoretical modelling as well as a reduction of 8 dB(A) by experimental testing at the Brussels tram network were reported.

Prediction of noise emission of rolling noise is quite often done based on a wheel-rail model presented by Remington. This SEA (Statistical Energy Analysis) Model has been implemented in several software packages such as TWINS or WR-Noise (see also D3.1/8). These softwares permit to calculate noise 1/3 octave noise spectra at some (7.5 m) distance from a track and provide contributions of rail, wheel, sleeper to the total noise as function of frequency.

Of course, those models require detailed information about sleeper, ballast, rail, rail pad and vehicle. The dynamic behaviour of the track is characterized by a set of transfer functions, which are calculated by means of finite element analysis.

2.2.2 Analytical model

The block diagram shown in Figure 2.2.1 summarises the analytical model used in the calculation software WR NOISE developed by D2S Int'l. This model, originally based upon the Remington model[1], has been adapted in order to be accurate in a frequency band up to 5 kHz.

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[1] Paul J. Remington, Wheel/rail rolling noise, I: Theoretical analysis, and II: Validation of the theory, *J. Acoust. Soc. Am.* **81 (6)**, 1805-1832, 1987.

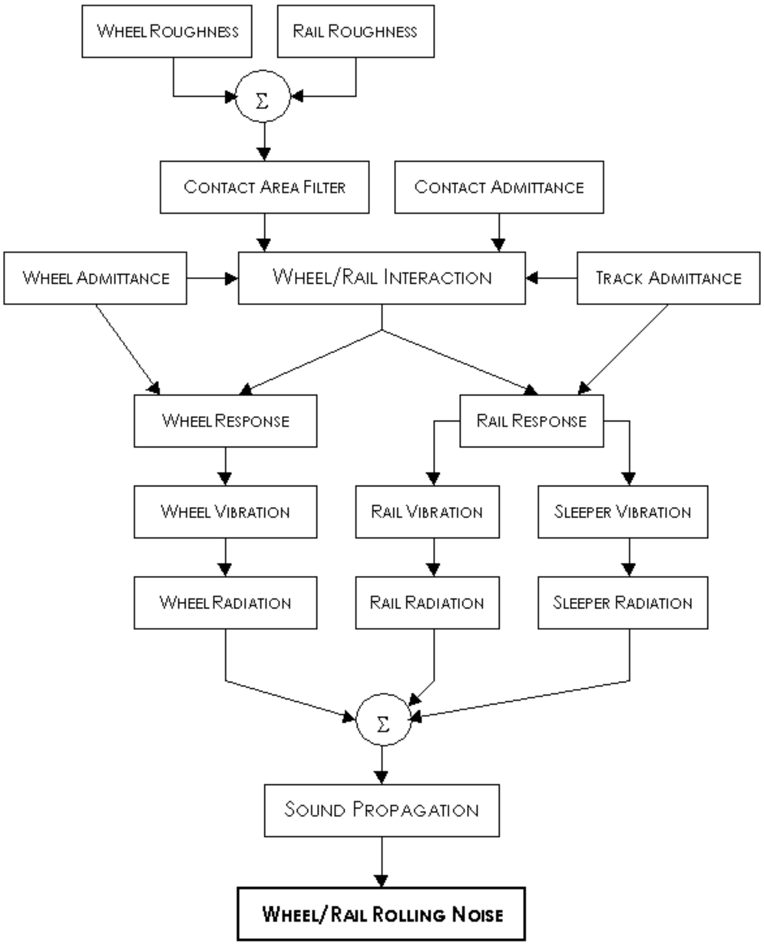

Figure 2.2.1

Block diagram of the analytical model

The model assumes that the small-scale roughness on the running surfaces of the wheel and rail is the primary mechanism for the noise generation. The combined roughness of wheel and rail multiplied by a contact filter that takes into account the finite area of contact between wheel and rail provides the input excitation to the wheel/rail interaction model.

This interaction model uses contact, wheel and rail admittances to calculate the wheel and rail response at the point of contact. From these responses and the wheel and rail admittance, the average vibration of the wheel and track components (rail and sleeper) are calculated.

Finally, the interaction results in sound radiation from the motion of the wheels and track components.

2.2.3 Actual interim calculation method (SRM II)

In the actual intern calculation method, the aspects of rail and wheel are included in the emission parameters. The emission values per rail vehicle are determined by:

$$E_c = a_c + b_c \lg v_c + 10 \lg Q_c + c_{b,c} \qquad 1$$

with b track type [-]

c	train category [-]
v_c	average speed of rail cars [km/h^{-1}]
Q_c	average quantity of non braking trains of the considered rail vehicle category [h^{-1}]
$C_{b,c}$	emission difference between a railway care on a track with concrete sleepers and one on another track type under identical circumstances (table 2.2.3)

The standard emission values a_c & b_c are given in table 2.2.1 in function of train category:

category	a_c	b_c
1 Block braked passenger trains	14.9	23.6
2 Disc braked and block braked passenger trains	18.8	22.3
3 Disc braked passenger trains	20.5	19.6
4 Block braked freight trains	24.3	20.0
5 Block braked diesel trains	46.0	10.0
6 Diesel trains with disc brakes	20.5	19.6
7 Disc braked urban subway and rapit tram trains	18.0	22.0
8 Disc braked InterCity and slow trains	25.7	16.1
9 Disc braked and block braked high speed trains	22.0	18.3

Table 2.2.1 Standard emission values as function of railway category c

The following types of tracks are also distinguished:

railway tracks	index code b
with single block or double block (concrete) sleepers, in ballast bed	1
with wooden or zigzag concrete sleepers, in ballast bed	2
in ballast with non-welded tracks, tracks with joints or switches	3
with blocks	4
with blocks and ballast bed	5
with adjustable rail fixation	6
with adjustable rail fixation and ballast	7
with poured in railway lines	8
with level crossing	

Table 2.2.2

For railway crossings, 2 dB are added to the value in table 2.2.3, according to the track type before and after the crossing. If these values differ, the construction with the highest value is used.

category	b=1	b=2	b=3	b=4	b=5	b=6[2]	b=7	b=8
1	0	2	4	6	3	-	0	2
2	0	2	5	7	5	-	0	3
3	0	1	3	5	2	-	0	2
4	0	2	5	7	4	-	0	2
5	0	1	2	4	4	-	0	2
6	0	1	3	5	2	-	0	2
7[3]	0	1	-	-	-	-	-	-
8	0	2	4	6	3	-	0	2
9	0	2	4	6	3	-	0	2

Table 2.2.3 Correction term $C_{b,c}$ as a function of railway category and track type b

category	description
1	block braked passenger trains
2	disc braked and block braked passenger trains
3	disc braked passenger trains
4	block braked freight trains
5	block braked diesel trains
6	diesel trains with disc brakes
7	disc braked urban subway and rapid tram trains
8	disc braked InterCity and slow trains
9	disc braked and block braked high speed trains
10	provisionally reserved for high speed trains of the ICE-3 (M) (HST East) type

Table 2.2.4

2.2.4 IMAGINE rail noise model

With the support of EU, two research projects were launched to develop a unified European Calculation Model for strategic noise mapping: HARMONOISE and IMAGINE.

Inside the IMAGINE project, a more detailed Rail Noise Model (close to the analytical model) has been developed. It is useful to evaluate its applicability for modelling rail noise mitigation measures.

Rolling noise

This proposal also separates the vehicle contribution and the track contribution to rolling noise for accuracy of propagation modelling, for apportionment of responsibility for environmental noise, and for cost-effective action planning. Further to this, because of the sensitivity of rolling noise to the “combined effective roughness” at the wheel-rail

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[2] tracks with b=6 are being further studied

[3] track of category 7 are also being studied

interface (i.e. the combined roughness at the contact between wheel and rail, taking into account filter effects at their interface), this roughness should be included as a causal parameter for rolling noise. The approach taken within IMAGINE has been to apply techniques developed within the EC projects "METARAIL" and "STAIRRS", considering rolling noise to be generated via the mechanism shown in Figure 2.2.2.

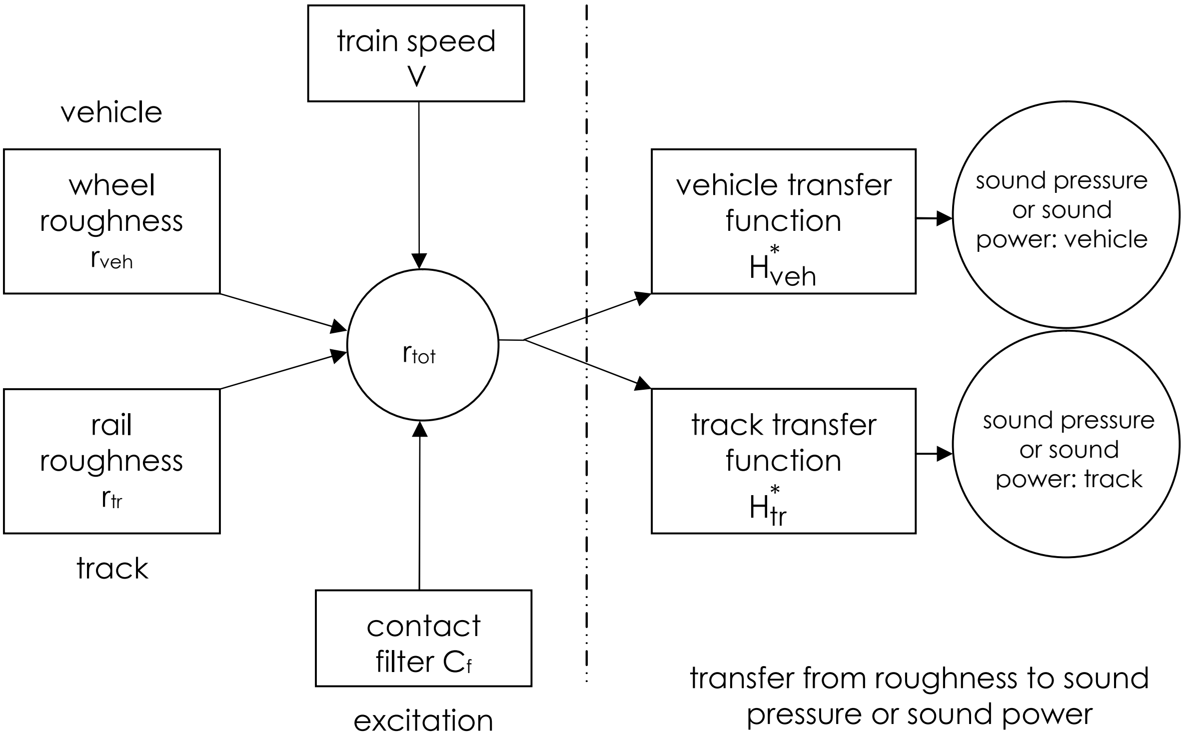


Figure 2.2.2

The mechanism of rolling noise generation applied within IMAGINE

This mechanism requires the contribution of the track and the vehicle to rolling noise to be quantified separately. From this, provided the combined effective roughness is known, transfer functions relating the vehicle contribution and the track contribution, separately, to this roughness, can be directly calculated for each 1/3 octave band of frequency. Techniques for carrying out this separation are outlined in the proposal. For rolling noise, therefore, the contributions from the track and from the vehicle are fully described by these transfer functions, provided the combined effective roughness is known. This roughness can be acquired either as a single value via pass-by measurements of track vibration, or by the use of direct measurements of wheel and rail roughness and the inclusion of contact filter effects. It are these transfer functions that are the core data relating to rolling noise within the IMAGINE Rail Noise Sources Database.

Rolling noise is calculated at axle height (vehicle contribution at 0.5 m above rail head) and rail head height (track contribution), and has as an input the total effective roughness $L_{r,tot,i,}(v)$ as a function of train speed v, the track and vehicle transfer functions $L_{Hpr,nl,tr,i}$ and $L_{Hpr,nl,veh,i}$ and the axle density (= number of vehicle * axles) N_{ax}/l_{veh}:

$$L_{peqi,roll}\ (h = 0\ m) = L_{rtot,i}\ (v) + L_{Hpr,nl,tr,i} + 10\ lg\ (N_{ax}/l_{veh}) \qquad 1$$

$$L_{peqi,roll}(h = 0{,}5\ m) = L_{rtot,i}\ (v) + L_{Hpr,nl,veh,i} + 10\ lg\ (N_{ax}/l_{veh}) \qquad 2$$

where N_{ax} is the number of axles per vehicle and l_{veh} the vehicle length.

If the roughness is obtained as a function of wavelength λ, it must be converted to the required speed using the relation λ = v/f, where f is frequency [Hz] and v is train speed in [m/s].

The transfer functions $L_{Hpr,nl,tr,i}$ and $L_{Hpr,nl,veh,i}$ are speed-independent. They have the reference unit of sound pressure squared per unit roughness squared, normalised to the axle density N_{ax}/l_{veh}. They are known from measurement or calculation for different track and vehicle types and are defined by:

$$\begin{aligned} L_{Hpr,nl,veh,i} &= L_{peq,veh,i}(v) - L_{rto,i}(v) - 10\lg\frac{N_{ax}}{l_{veh}} \\ L_{Hpr,nl,tr,i} &= L_{peq,tr,i}(v) - L_{rto,i}(v) - 10\lg\frac{N_{ax}}{l_{tr}} \end{aligned} \qquad 3$$

where $L_{peq,veh,i}(v)$ and $L_{peq,tr,i}(v)$ are the vehicle and track noise contributions in the sound pressure level, i is the frequency band number, v is the speed, $L_{rtot,i}(v)$ is the combined effective roughness at speed v.

Rolling noise is speed dependent and is therefore relevant for the operating conditions constant speed, acceleration, deceleration and curving. It is practical to work with effective roughness as it is related directly to the real excitation. Effective roughness is related to direct roughness via the contact filter $A_3(l)$:

$$L_{rtr}(l) = L_{rtr,dir}(l) + A_3(l) \qquad 4$$

The track transfer function can also be used in the same way for noise from bridges or for non standard track support structures (e.g. slab track). For steel bridges it will tend to be significantly higher than for normal tracks. Bridge noise is included in the rolling noise source by using a track transfer function at h = 0 m including the track and the bridge.

2.2.5 Conclusion

In the next paragraphs, the usefulness of different modelling theories will be studied for each of the mitigation measures.

2.3 MITIGATION MEASURES FOR WHEELS

Reference to D6.2: GM-Rail -1

Resilient wheels are known to reduce the noise emission with 1 or 2 dB(A).

2.3.1 Analytical model

When regarding the analytical model (WR-Noise, TWINS) as discussed in §2.2.2, this seems very logical. A modified (more dampened) wheel admittance will lead to a reduced amplitude of the wheel response, hence a reduced wheel vibration level will be obtained.

This approach also has been validated by a comparison between calculated and measured noise level inside the QCITY report (deliverable D3.1.7).

2.3.2 SRM II model

In the SRM II model (= the actual method for strategic noise mapping) only different types of vehicles are defined, including only one tram/metro type vehicle. Of course, this is insufficient to take smaller modifications on the wheel emission into account.

On the other hand, the method differentiates well between the wheel (source at height of 0.5 m) and the rail (source at a height of 0.0 m). Thus, an arbitrary reduction of the wheel could be introduced. But this approach is not foreseen nor described in the method.

2.3.3 IMAGINE model

The IMAGINE model seems well suited for taking into account a modified wheel response, becomes a specific parameter (§2.2.4), $L_{H\ pr,nl,veh,l}$, the vehicle transfer function is included in the model. This parameter can be obtained by measurement or by calculation (analytical model).

But it also may not be forgotten that also the parameter $L_{z\ tot,l}$, the total effective roughness will be modified by different wheel characteristics.

2.3.4 Conclusion

It can be expected that future noise mapping methods will have the possibility to include modified wheel transfer functions, hence modified wheel behaviour and radiation.

2.4 MITIGATION MEASURES FOR RAILS

Mainly following aspects will be discussed:

- rail damping: reference to D6.2: GM-Rail -3/4/5/7/8
- embedded rails: reference to D6.2 – GM-Rail -6

Several mitigation measures exist to reduce radiation of the rail, such as:

- track types and damping;
- embedded rail;
- rail types.

2.4.1 Analytical model

When regarding the analytical model, §2.2.2, this seems very logical. A modified (more dampened) rail admittance will lead to a reduced amplitude of the rail response, hence a reduced rail vibration level will be obtained.

2.4.2 SRM II model

In the SRM II model (actual EU method for strategic noise mapping) 8 different types of tracks (see §2.2.3, table 2.2.2) are defined, each of them with a different spectral (octava bands only) correction. But thought exists about the accuracy of the spectral corrections, also in the light of the multitude of new special types of tracks coming onto the market.

Further, it is also known that the there is sometimes an interaction between rail and wheel. This is taken partially taken into account by the definition of the source for which difference is made between the wheel (source at height of 0.5 m) and the rail (source at a height of 0.0 m). But as there is only one type of tram/metro vehicle described, it is doubtfull that this is sufficient.

2.4.3 IMAGINE model

The IMAGINE model seems well suited for taking into account a modified track response, becomes a specific parameter (§2.2.4), $L_{H\ pr,nl,tr,l}$, the track transfer function is included in the model. This parameter can be obtained by measurement (spectral 1/3 octave band) or by calculation (analytical model).

But it also may not be forgotten that also the parameter $L_{z\ tot,l}$, the total effective roughness will be modified by different rail characteristics.

This model is thus completely capable of taking into account all new types of rail mitigation measures. For the time being, it can be proposed to use a spectral (octave) correction to the trackbed emission correction function.

2.5 TRACKBED ABSORPTION

Reference to D6.2: GM-Rail -2

Trackbed absorption is known to yield a reduction of 2 to 5 dB(A), depending on type and/or environment.

2.5.1 Analytical model

From a theoretical point of view, the trackbed impedance or absorption could be deducted or measured. Based on a nearfield reflection model, residual radiation could be determined.

But when looking at the propagation models used, trackbed absorption should be part of the emission model. Absorption or surface characteristics near the source are not included in the propagation model.

2.5.2 SRM II model

The SRM II model (the actual EU method for strategic noise mapping) contains 8 different types of tracks (see §2.2.3, table 2.2.2), each of them with a different spectral (octava bands only) corrections. To these values, correction are added for level crossings or switches. Trackbed absorption is not described, but a similar correction (reduction) could be added.

2.5.3 IMAGINE model

The IMAGINE model does not include a specifc correction term for trackbed absorption. This could be included in the track response transfer function , $L_{H\ pr,nl,tr,l}$, but this is not foreseen as such.

It seems better to use the general correction transfer function of the global outcome $L_{p,eq}$. This parameter can be obtained by measurement (spectral 1/3 octave band) of the difference between measurements on a reference track and the “absorptive” track with the same vehicle.

2.6 WHEEL AND RAIL GRINDING

Reference to D6.2: GM-Rail -8/9

2.6.1 Discussion

Sensitivity analysis carried out for tram and metro network indicated that wheel and rail roughness is the most important parameter to reduce noise emission at a given speed.

Reductions up to 15 dB were indicated by both theoretical modelling as well as a reduction of 8 dB(A) by experimental testing at the Brussels tram network were reported.

Prediction of noise emission of rolling noise is quite often done based on a wheel-rail model presented by Remington. This SEA (Statistical Energy Analysis) Model has been implemented in several software packages such as TWINS or WR-Noise (see also D3.1/8). These softwares permit to calculate noise 1/3 octave noise spectra at some (7.5 m) distance from a track and provide contributions of rail, wheel, sleeper to the total noise as function of frequency.

Of course, those models require detailed information about sleeper, ballast, rail, rail pad and vehicle. The dynamic behaviour of the track is characterized by a set of transfer functions, which are calculated by means of finite element analysis.

2.6.2 Actual Interim Calculation Method

As the Interim Calculation Method is based on SRM II – 1996, in which no correction for rail roughness is available, this aspect is not retained in the actual AR-Interim Method.

But as this aspect is generally recognized to be important, the WG-AEN "*Guide of good practice*", recommends taking this aspect into consideration.

2.6.3 Proposal of RMR 2004

The new Dutch proposal for adaptation of the Rail Calculation Method (versions RMR 2002 and 2004, but not yet approved) has following proposal for the modelling of wheel and rail roughness.

The extra noise emission of a rough track or the noise reduction of a smoother track will be included for existing categories by integration of the difference in the energetic sum of wheel and track roughness in the correction for the track characteristics.

This methodology is only correct for a jointless track (m = 1). This parameter is also dependent on speed (v) and train category (c).

A trackbed correction value $C_{c,bb,i,m}$ will be calculated for different train categories by:

$$C_{c,bb,i} = C_{c,bb,i} - \left(L_{i,rtr,ni}(\lambda_i) \oplus L_{i,rveh,c}(\lambda_i)\right) + \left(L_{i,rtr,loc}(\lambda_i) \oplus L_{i,rveh,c}(\lambda_i)\right) \qquad 5$$

with:	$C_{bb,i}$	the basic track correction
	$L_{i,rtr,nl}(\lambda_i)$	average rail roughness in the reference country (Netherlands), table 2.6.2
	$L_{i,rtr,loc}(\lambda_i)$	local rail roughness of the track on which the calculations are being carried out
	$L_{i,rveh,c}(\lambda_i)$	wheel roughness of different train categories, according to table 2.6.1
	$\oplus$	energetic summation

The rail roughness of the local situation is measured at representative locations and integrated in the model. These locations have to be selected from the total length of the track that will be included in the model. These locations have to be specified in the measurement report.

If calculations are carried out with a lower value of rail roughness than average, the track exploitation company has to guarantee that, by monitoring and additional grinding, the low rail roughness level can be maintained.

Determinant for this is that the differences in rail roughness, averaged over the considered part of the track and the calculated total noise emission per train category, (sum of all source heights and octave bands) remain equal to the value of the original calculation, and that the local increase per train category is limited to maximum 1 dB(A).

wavelength [cm]	wheel roughness in function of brake system			
	disc brake + blocks	only disc brakes	cast-iron block brake	disc brake + added cast-iron block brake
20.2	-3	8	5	11
16	-4	7	6	11
12.7	-3	7	7	12
10.1	-2	6	9	13
8	-1	6	11	14
6.3	-2	3	13	16
5	-1	1	12	15
4	-2	-1	10	12
3.2	-2	-2	8	11
2.5	-3	-3	6	10
2	-3	-3	5	6
1.6	-3	-4	0	3
1.3	-4	-4	-1	-2
1	-5	-5	-1	-5
0.8	-7	-7	-3	-7

Table 2.6.1 Data to determine rail roughness, according to the type of brake system in function of the wavelength

For the nine categories in this standard, the following relation between brake system and train category applies:

categories 1, 4, 5, 7 & 9:	pushed units: cast-iron block brake;
category 2:	disc brake + added block brake;
categories 3, 6, 8 & 9:	pulled units: disc brake.

The disc brake system with added block brakes is currently unavailable in the Netherlands, but its introduction is always possible.

For new train categories that are being measured according to ISO3095 or to SRM II 2004, the average wheel roughness has to be determined by measurements.

If wheel and rail roughness are expressed in 1/3 octave bands, they are transposed to octave bands for SRM II calculations.

Over the years, the Dutch national average reference rail roughness is defined $L_{rtr,natref}(\lambda)$ where λ is the wavelength in cm, table 2.6.2.

wave length [cm]	REF avg REFERENCE [-]
16	7.0
12.5	6.0
10	5.0
8	4.0
6.3	3.0
5	2.0
4	1.0
3.15	0.0
2.5	-1.0
2	-2.0
1.6	-3.0
1.25	-4.0
1	-5.0
0.8	-6.0
0.63	-7.0
0.5	-8.0
0.4	-9.0
0.315	-10.0
0.25	-11.0
0.2	-12.0
0.16	-13.0
0.13	-14.0
0.1	-15.0

Table 2.6.2 Dutch national roughness spectrum as function of wavelength

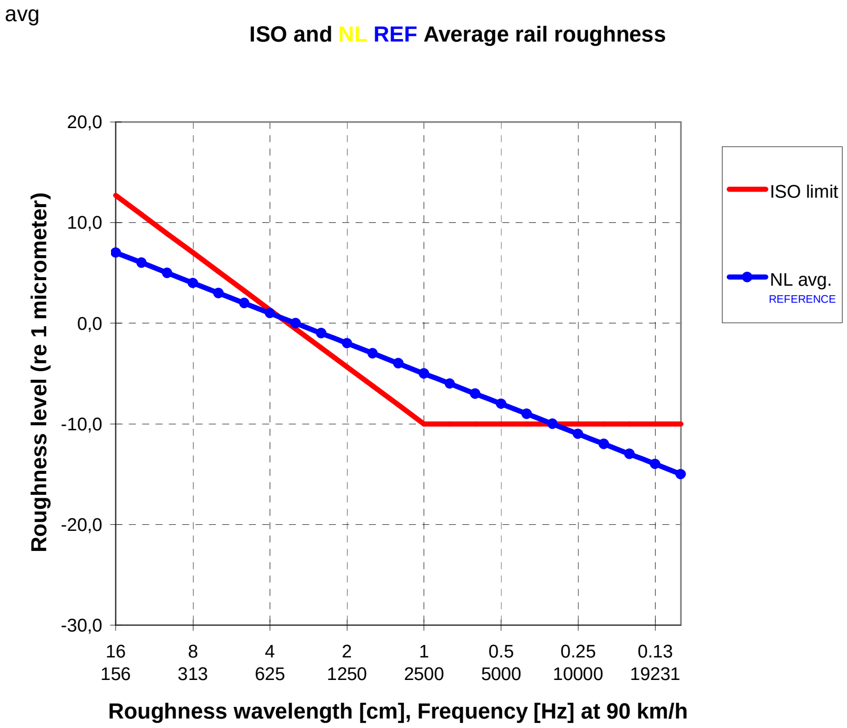


Figure 2.6.3

Average rail roughness of the Dutch rail network - Reference rail roughness and the EN ISO 3095 limit curve for rail roughness at a test site

2.6.4 Proposal of IMAGINE Rail Noise Model

Rolling noise

This proposal also separates the vehicle contribution and the track contribution to rolling noise for accuracy of propagation modelling, for apportionment of responsibility for environmental noise, and for cost-effective action planning. Further to this, because of the sensitivity of rolling noise to the "combined effective roughness" at the wheel-rail interface (i.e. the combined roughness at the contact between wheel and rail, taking into account filter effects at their interface), this roughness should be included as a causal parameter for rolling noise. The approach taken within IMAGINE has been to apply techniques developed within the EC projects "METARAIL" and "STAIRRS", considering rolling noise to be generated via the mechanism shown in Figure 2.6.4.

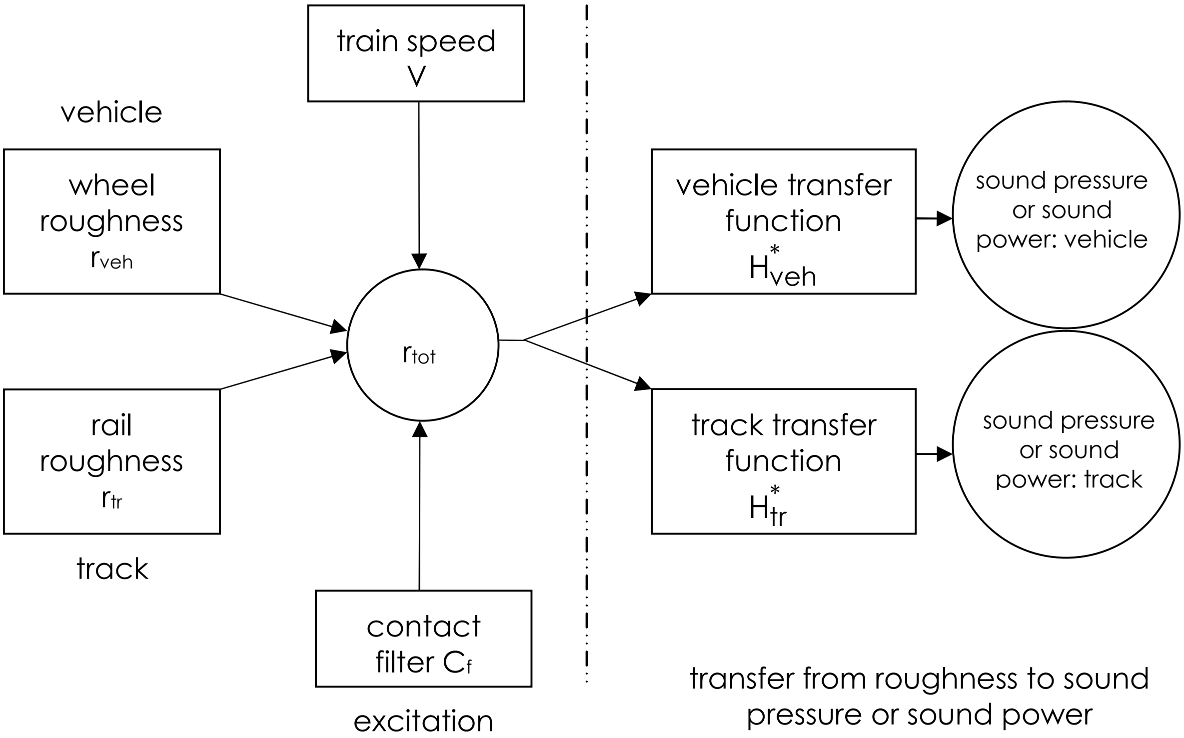


Figure 2.6.4

The mechanism of rolling noise generation applied within IMAGINE

This mechanism requires the contribution of the track and the vehicle to rolling noise to be quantified separately. From this, provided the combined effective roughness is known, transfer functions relating the vehicle contribution and the track contribution, separately, to this roughness, can be directly calculated for each 1/3 octave band of frequency. Techniques for carrying out this separation are outlined in the proposal. For rolling noise, therefore, the contributions from the track and from the vehicle are fully described by these transfer functions, provided the combined effective roughness is known. This roughness can be acquired either as a single value via pass-by measurements of track vibration, or by the use of direct measurements of wheel and rail roughness and the inclusion of contact filter effects. It are these transfer functions that are the core data relating to rolling noise within the IMAGINE Rail Noise Sources Database.

Rolling noise is calculated at axle height (vehicle contribution at 0.5 m above rail head) and rail head height (track contribution), and has as an input the total effective roughness $L_{r,tot,i,}(v)$ as a function of train speed v, the track and vehicle transfer functions $L_{Hpr,nl,tr,i}$ and $L_{Hpr,nl,veh,i}$ and the axle density (= number of vehicle * axles) N_{ax}/l_{veh}:

$$L_{peqi,roll}\,(h = 0\ m) = L_{rtot,i}\,(v) + L_{Hpr,nl,tr,i} + 10\ \lg\,(N_{ax}/l_{veh}) \tag{6}$$

$$L_{peqi,roll}\,(h = 0{,}5\ m) = L_{rtot,i}\,(v) + L_{Hpr,nl,veh,i} + 10\ \lg\,(N_{ax}/l_{veh}) \tag{7}$$

where N_{ax} is the number of axles per vehicle and l_{veh} the vehicle length.

If the roughness is obtained as a function of wavelength λ, it must be converted to the required speed using the relation $\lambda = v/f$, where f is frequency [Hz] and v is train speed in [m/s].

The transfer functions $L_{Hpr,nl,tr,i}$ and $L_{Hpr,nl,veh,i}$ are speed-independent. They have the reference unit of sound pressure squared per unit roughness squared, normalised to the axle density N_{ax}/l_{veh}. They are known from measurement or calculation for different track and vehicle types and are defined by:

$$L_{Hpr,nl,veh,i} = L_{peq,veh,i}(v) - L_{rto,i}(v) - 10\lg\frac{N_{ax}}{l_{veh}}$$
$$L_{Hpr,nl,tr,i} = L_{peq,tr,i}(v) - L_{rto,i}(v) - 10\lg\frac{N_{ax}}{l_{tr}} \qquad 8$$

where $L_{peq,veh,i}(v)$ and $L_{peq,tr,i}(v)$ are the vehicle and track noise contributions in the sound pressure level, i is the frequency band number, v is the speed, $L_{rtot,i}(v)$ is the combined effective roughness at speed v.

Rolling noise is speed dependent and is therefore relevant for the operating conditions constant speed, acceleration, deceleration and curving. It is practical to work with effective roughness as it is related directly to the real excitation. Effective roughness is related to direct roughness via the contact filter $A_3(l)$:

$$L_{rtr}(l) = L_{rtr,dir}(l) + A_3(l) \qquad 9$$

The track transfer function can also be used in the same way for noise from bridges or for non standard track support structures (e.g. slab track). For steel bridges it will tend to be significantly higher than for normal tracks. Bridge noise is included in the rolling noise source by using a track transfer function at h = 0 m including the track and the bridge.

2.6.5 Evaluation

For a given track, the influence of modified track and/or wheel roughness is identical (subtraction of the original combined total roughness and adding the new combined total roughness):

RMR2004

$$\Delta L = -(L_{i,rtr,org} \oplus L_{i,rvel,org}) + (L_{i,rtr,mod} \oplus L_{i,rvel,mod})$$

IMAGINE

$$\Delta L = L_{rtot,org} - L_{rtot,mod}$$

with: $L_{rtot} = L_{rveh} \oplus L_{rtrack} + A_3$

(Although in the global calculation, an additional "contact filter": A_3 is included in the new "IMAGINE"-model, for a given track and speed, this effect is added out.)

The evaluation of the sensitivity to roughness has been carried out on a model of a part of the city of Ghent (area of 3820 inhabitants).

The number of annoyed people above:

- L_{den}: 55 dB(A) is 1300;
- L_{night}: 45 dB(A) is 1700.

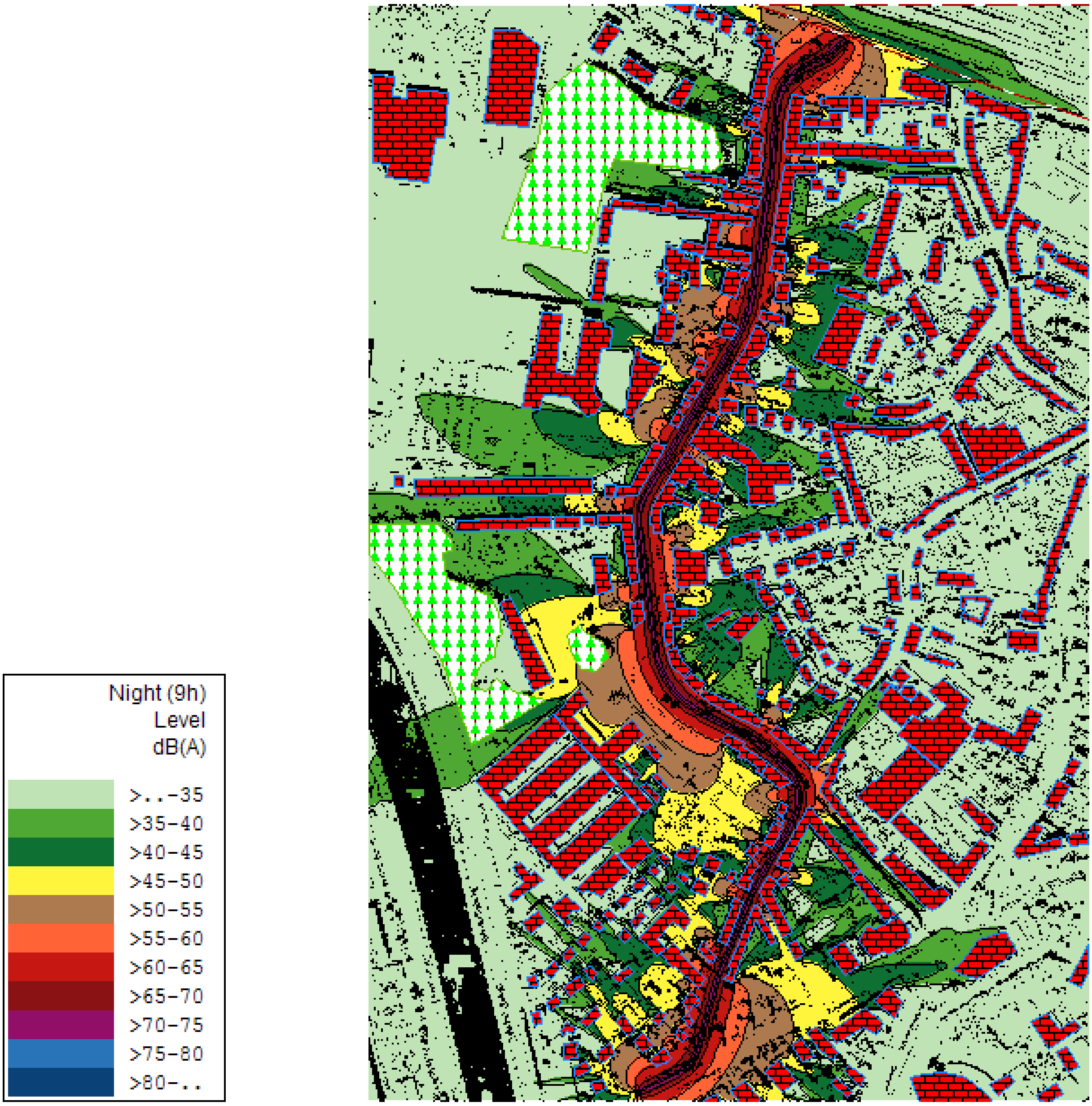


Figure 2.6.5

Following improvements are evaluated:

- rail roughness;
- wheel roughness.

Rail roughness

Initial roughness was approximately 10 – 15 dB above recommended (ISO) roughness. It has been reduced by grinding. The results of these grindings are OK at lower frequencies (up to 250 Hz ~6.3 cm wavelength) but above that frequency, results are more than 5 dB worse than recommended ISO or NL-standard (figure 2.6.6 – frequencies calculated for 60 km/h).

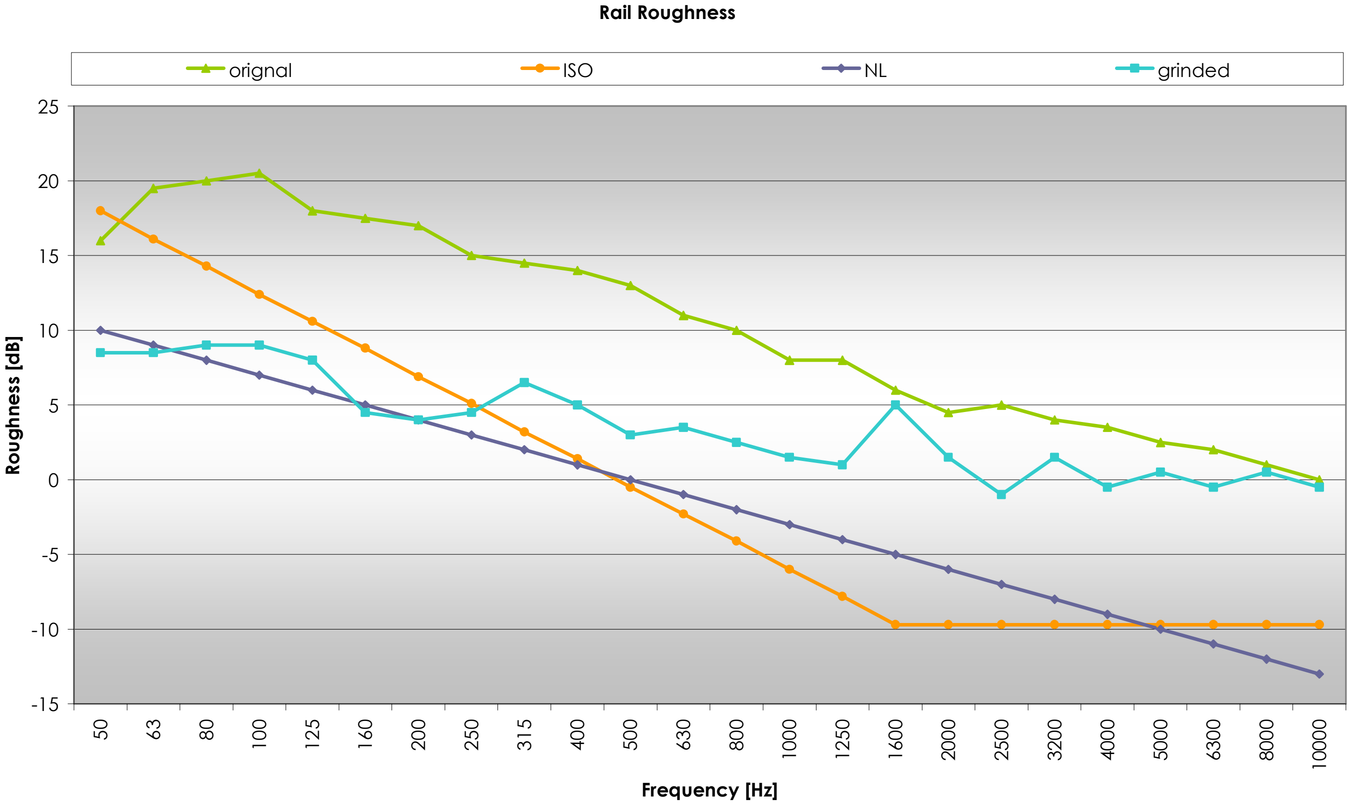


Figure 2.6.6

Wheel roughness

Initial wheel roughness is known to be average. Two types of smoother wheels are evaluated (figure 2.6.7):

- maximum grinding and installation of disc braking: up to 10 dB improvement at the low frequencies and up to 5 dB improvement at the higher frequencies.
- high frequency grinding: only improving rail performance above 160 Hz.

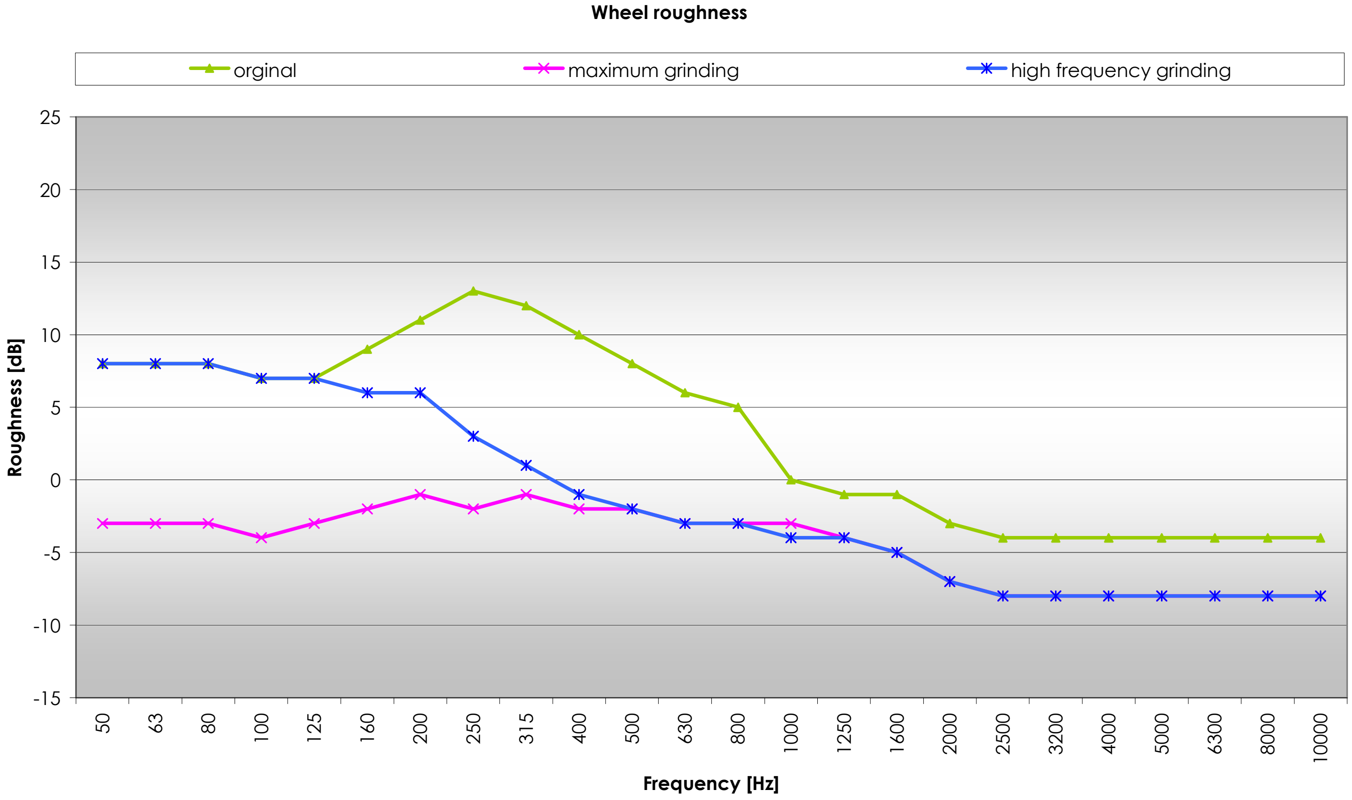


Figure 2.6.7

The combined effect of rail and wheel compared to the original situation is given in figure 2.6.8. The initial situation (rail + wheel) is set as a reference. Further results are combined to octave bands, to be used in the Dutch AR-Interim Calculation Method.

It can be seen that:

- actual grinding of the rail gives little improvement above 1000 Hz;
- NL rail quality and actual grinding give important improvement in the low frequencies;
- little difference of combined roughness of wheel grinding in low frequencies in combination with ISO rail quality, but more than 5 dB in middle frequencies.

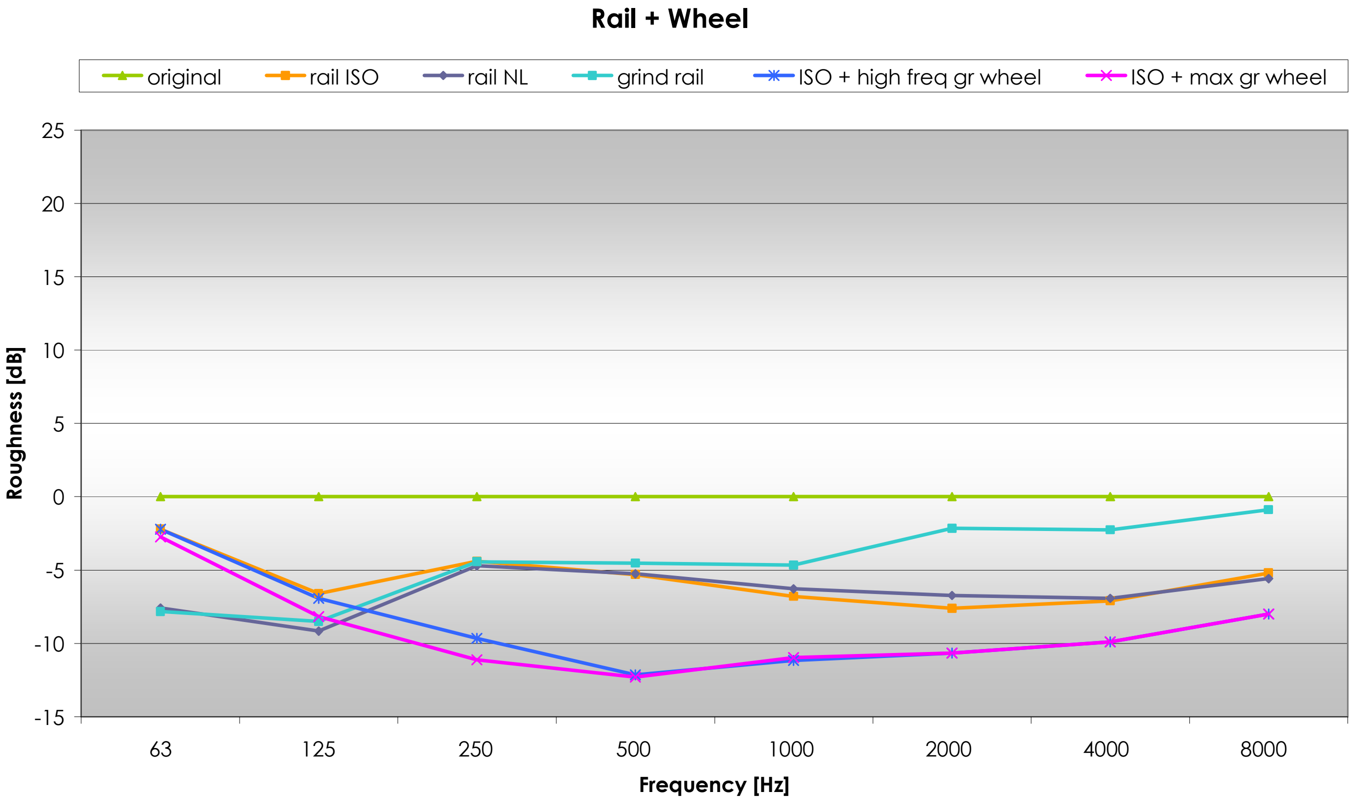


Figure 2.6.8

Evaluation based on the reduction of the number of annoyed indicates:

- actual realised grinding is less effective than recommended standards ISO/NL;
- NL and ISO rail standard lead to similar results;
- higher frequency wheel grinding (> 160 Hz) is sufficient in combination with ISO rail grinding;
- both effects together give an improvement of more than 10 dB (= two classes of improvement).

Variant:	Rail	REF REF	rail: ISO wheel: ref	rail: NL wheel: ref	rail: grinding wheel: ref	rail: ISO wheel: max grind	rail: ISO wheel: high freq grind
Noise index							
DEN (24h)	... < Lden < 55 dB	2522	2823	2823	2775	2900	2889
	55 <= Lden < 60 dB	297	77	66	97	475	486
	60 <= Lden < 65 dB	66	498	486	175	445	445
	65 <= Lden < 70 dB	348	422	445	773	0	0
	70 <= Lden < 75 dB	587	0	0	0	0	0
	75 <= Lden <... dB	0	0	0	0	0	0
	Sum	3820	3820	3820	3820	3820	3820
Night (9h)	... < Ln < 45 dB	2125	2616	2568	2522	2823	2823
	45 <= Ln < 50 dB	416	211	255	282	77	77
	50 <= Ln < 55 dB	282	73	77	81	636	628
	55 <= Ln < 60 dB	62	680	628	172	284	292
	60 <= Ln < 65 dB	486	240	292	763	0	0
	65 <= Ln < 70 dB	449	0	0	0	0	0
	70 <= Ln <... dB	0	0	0	0	0	0
	Sum	3820	3820	3820	3820	3820	3820

Table 2.6.3

Measurements on site reported a higher noise reduction (-7 to -8 dB) for the rail grinding. This means that the real wheel quality will be better than estimated. In the above analysis, the effect of improved grinding (±10 dB) has been levelled out by the rough wheel quality to an averaged overall roughness improvement of 4 to 5 dB.

Evaluation based on Noise Rating Source

To be done.

2.6.6 Conclusion

The proposed methodology in RMR2004 and IMAGINE calculation models is almost identical and based on a 1/3 octave band spectral correction factor.

This correction factor is based on both wheel and rail roughness which should have both approximately similar quality. Otherwise, improvement of one element is levelled out by the bad quality of the other element.

For urban track at lower speeds (60 – 120 km/h), the important wavelengths are situated around 1 – 4 cm wavelength: special attention must be drawn to the fact that "acoustical grinding" should concentrate on those frequencies and not only on the higher wavelengths.

2.7 DEFECTS/JOINTS

Reference to D6.2: GM-Rail -11/12/13/14

2.7.1 Discussion

Impact noise is generated at rail joint gaps and elevation discontinuities. Large joint gaps create more noise than short joint gaps. Also misalignment of the running surface elevation will result in impact noise. Thus, joint maintenance includes tightening rail joints to remove or reduce gaps, aligning running surface elevations and repairing battered ends.

2.7.2 Theoretical emission model

The dynamic force generated at the wheel-rail contact by an impact can be schematised by an equivalent wheel flat. For this study, the paper titled “Wheel rail noise - part III: Impact noise generation by wheel and rail discontinuities”, Journal of Sound and Vibration, Vol. 46, 395-417, 1976, by Ver, Ventres and Myles, is used as a reference.

The first step is to calculate the critical speed, i.e. the rolling speed at which rail and wheel will be separated from each other. For an elastic rail, the critical speed can be expressed as:

$$V_{CR} = \sqrt{ga\left(1+\frac{M}{m}\right)}\sqrt{1+\frac{m}{\rho l}\frac{\beta}{2}}$$

with	g	gravity constant $[m/s^2]$	
	a	wheel radius [m]	
	M	part of the vehicle mass, supported resiliently by the wheel [kg]	
	m	not suspended wheel mass [kg]	
	ρl	mass per unit length of the rail [kg/m]	
	β	$=\left(\frac{K}{4EI}\right)^{\frac{1}{4}}$	
	with	K	foundation stiffness per rail unit length [N/m/m]
		E	elasticity modulus $[N/m^2]$
		I	inertia moment of the transversal rail section $[m^4]$

For a circulation speed equal to the critical speed, the impulse I_m, due to a wheelflat, can be written as:

$$I_m = 2Y_0 m_{eq}\omega_0 \sin\left(\sqrt{\frac{2h}{Y_0}}\right)$$

where Y_0 static deflection of the rail under wheel load

ω_0	resonant frequency [rad/s] of the resiliently supported rail (not loaded)
h	height difference of the wheel flat [mm]
m_{eq}	equivalent impact mass of the resiliently supported rail [kg]

The obtained impulse needs to be converted into an impact force, acting on the railhead, and into a time history.

Emission transfer function

The emission transfer function contains:

- modelling of track system (rail, sleeper, trackbed in ballast or on concrete);
- modelling of soil interaction;
- modelling radiation.

This part of the transmission paths can be modelled by classical FEM or can be part of larger, more sophisticated models for the complete transmission paths.

Major research work is actually one at several universities to validate sophisticated software (FEM: structure; BEM: soil).

But as the source and the emission paths involve quite some uncertainties and because all details of the vibration generation process have not always to be known, a more general approach is often used.

2.7.3 AR-Interim Method

For track types with joints, the correction factor for track types is based on:

$$C_{bb,i,m} = C_{3,i} + 10\log(1 + f_m A_i) \tag{10}$$

with:	$C_{bb,i}$	general track correction from table 2.7.1
	f_m	table 2.7.2
	A_i	table 2.7.3

octave band [Hz]	$C_{3,i}$
63	1
125	3
250	3
500	7
1000	4
2000	2
4000	3
8000	4

Table 2.7.1 Correction factor $C_{bb,i}$ as a function of structures above station compounds/railway track condition (bb) and octave band (i)

The factor f_m can take on the following values, where m does not equal 1:

description	m type	f_m
track with rail joints	2	1/30
1 switch	2	1/30
2 switches per 100 m	3	6/100
more than 2 switches per 100 m (depot)	4	8/100

Table 2.7.2

octave band [Hz]	A_i
63	3
125	40
250	20
500	3
≥ 1000	0

Table 2.7.3 Code index for noise emission in the case of impact A_i as a function of the octave band (i)

On can deduct that for one switch per 100 m, the increase will be 0.4 dB at 63 and 500 Hz, 2 dB at 250 Hz and 4 dB at 125 Hz.

This is clearly arbitrary, as it is independent of the severity of the gap, and its an average for 100 m of track.

2.7.4 Future Method (IMAGINE)

The IMAGINE project recognizes that impact noise can vary in magnitude and can dominate over rolling noise. As it is often localised, it has to be taken into account when choosing track segmentation.

If present, impact noise is included in the rolling noise term by (energy) adding a supplemental roughness to the effective combined roughness:

$$L_{rtot}(\lambda) = L_{rveh}(\lambda) \oplus L_{rtr}(\lambda) \oplus L_{rimpact}(\lambda) \qquad 11$$

With L_{rveh} effective vehicle roughness
L_{rtr} effective track roughness

Impact noise will depend on the severity and number of impacts per unit length or joint density n_l, so the impact roughness can be given as:

$$L_{rimpact}(\lambda) = L_{rimpact,nl}(\lambda) + 10\,\lg(n_l/0.01) \qquad 12$$

where $L_{rimpact,nl}(\lambda)$ is the normalised impact roughness level and n_l is the joint density. The default impact roughness is given for a joint density $n_l = 0.01$, which is 1 impact per 100 m track. Situations with different numbers of joints can be approximated by adjusting the joint density n_l.

It is indicated that a different joint severity can be obtained by increasing the impact roughness level by approximately 20 log h (h is the step height of the joint). But no further information is given, on the reference height or gap.

It should be noted that when modelling the track layout and segmentation, the rail joint density should be taken into account, i.e. it may be necessary to take a separate source segment for a stretch of track with points.

2.7.5 Sensitivity analysis

In the IMAGINE model, reference values are given for the effective roughness and the influence of impact noise.

One can observe important differences between smooth tracks and areas with impacts. Impact noise can be compared by wheel/rail noise generated by vehicles with cast iron block brakes, figure 2.7.1

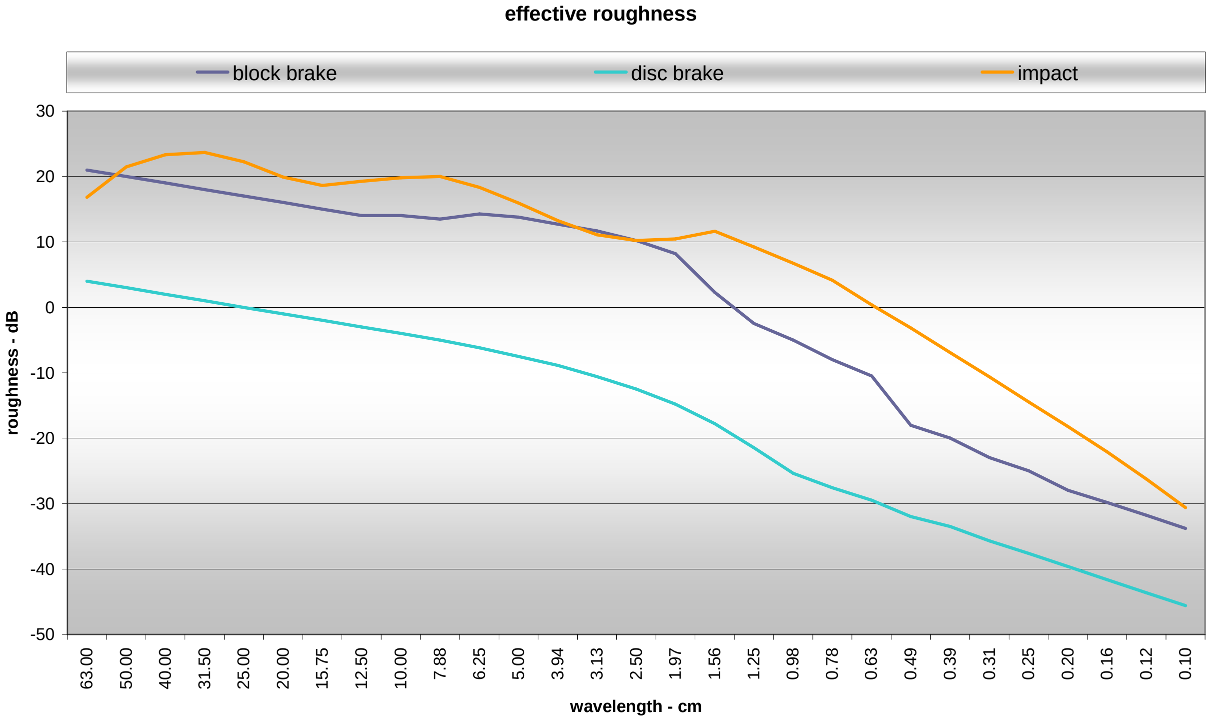


Figure 2.7.1

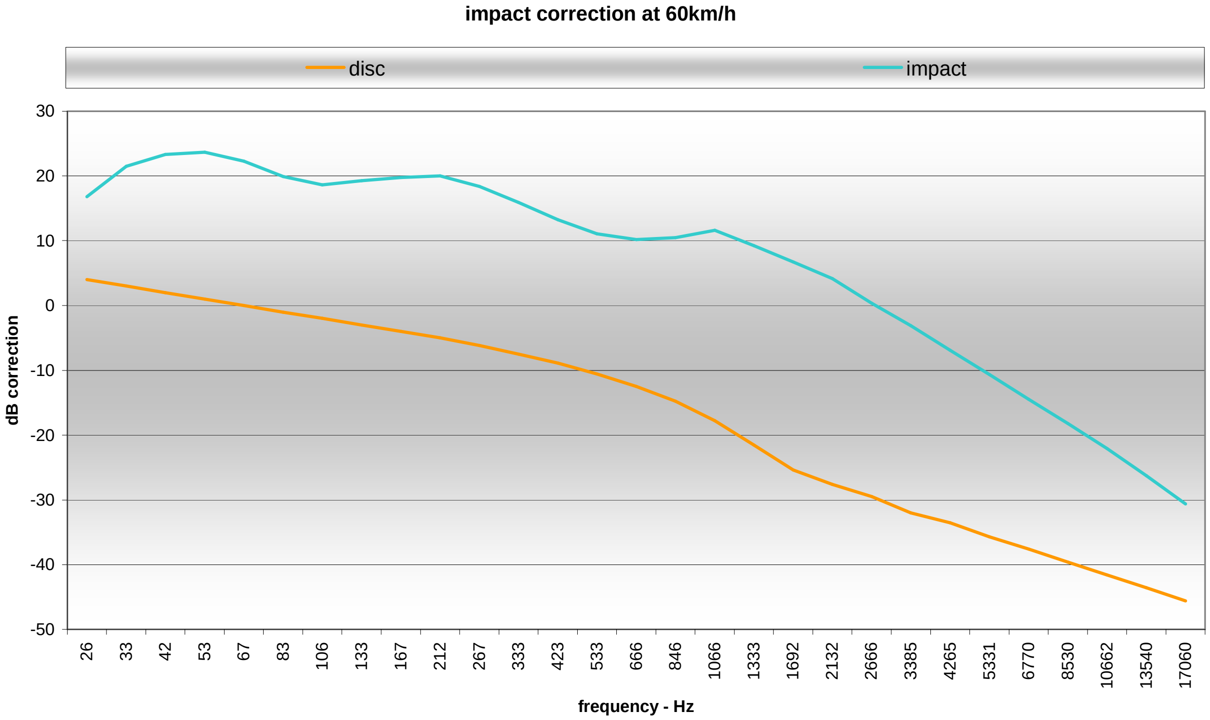


Figure 2.7.2

2.7.6 Conclusion

Impact noise is taken into account in noise modelling, but only in a very arbitrary way.

It should be better to add a point source or local source at the exact position of the defect/joint. This seems not more difficult or cumbersome as the actually proposed method, which asks lots of work for a very average and approximate result.

2.8 CORRUGATION: FRICTION MODIFICATION

Reference to D6.2: GM-Rail -15

2.8.1 Introduction

Corrugation is caused by the high friction forces between rail and wheel. This can be caused by rail and wheel imperfections (tangent track) but more easily in curved track (in the lower rail).

There forces are modulated by resonance frequencies of track and wheelset.

Under normal conditions, corrugation amplitude growth is moderate: amplitude of 0.05 mm in 1 year time, but the amplitude grows exponentially.

Rail grinding (see §2.6) is a preventive measure to control wear corrugation growth an to remove corrugation.

But another important measure for reducing wear corrosion is the use of railhead friction modifiers: the friction modifier reduces the friction forces (up to factor 2) and reduces stick-slip but does not change the vertical pressure in the wheel/rail contact. Actual data are not conclusive and therefore this will not be discussed further in this document.

2.8.2 Acoustical modelling

As corrugation can be regarded as excessive and layer wavelength wheel/rail wear, it can be assessed immediately by wheel/rail roughness measurements. These can be included in recent acoustical models as discussed in §2.6.

2.9 CURVE NOISE BY WHEEL DAMPERS

Reference to D6.2: LC-Rail -1/2/3/4

2.9.1 Discussion

Wheel squeal is the most common form of curving noise, caused by stick-slip oscillation during lateral slip of the tread over the railhead, and may be excruciating to patrons or pedestrians. Wheel howl at curves may be related to oscillation at the wheel's lateral resonance on the axle, caused by lateral slip or flange/rail contact during curving. At short radius curves where train speeds may be limited to 20 km/h, rolling noise may be insignificant relative to wheel squeal. At slightly curved track, normal rolling noise, excessive rolling noise due to roughness and corrugation, and impact noise due to rail defects and undulation are similar to those at tangent track, and the user is referred to the section on tangent track for discussion of noise not directly related to curving. Thus, the discussion of curving noise control presented below focuses on wheel squeal and wheel rail howl.

A link has been established with the EC Research Project SQUEAL BRPR-CT97-0477.

Wheel squeal originates from frictional instability (stick-slip), amplified by the wheel web. These problems can be studied by non-linear friction elements inside classical finite element models.

Out the results of recent studies reveal a combination of factors which, appear to control or eliminate wheel squeal at embedded track. These are:

1. use of resilient wheels or wheel dampers;
2. wheel & track lubrication.

The radiated sound power by the wheel during squeal can be calculated as:

$$L_W = 10\log\frac{\phi\rho c A u_0^2}{10^{-12}} \qquad 13$$

where ϕ is the radiation efficiency
ρc is the air impedance
A is the wheel radiating area
u_0 is the wheel vibration velocity

As a first approximation, and for a track in open air without major screen effect, the squeal sound pressure level can be calculated by:

- $SPL = L_w - 10\log(2\pi d^2)$ for reflecting ground
- $SPL = L_w - 10\log(4\pi d^2)$ for absorbing ground

2.9.2 Lumped parameter model with non-linear friction element

Justification of the model

Wheel squeal originates from frictional instability in curves between the wheel and rail. Stick-slip oscillations (more accurately referred to as roll-slip) are amplified by the wheel web. The accepted model for tram systems with resilient wheels involves Top Of Rail (TOR) frictional instability under lateral creep conditions leading to excitation of out of plane wheel bending oscillations. These are radiated and heard as squeal. The starting point for squeal is lateral creep forces that occur as a bogie goes through a curve and the wheel / rail contact patch becomes saturated with slip (creep saturation). A critical component in all the modelling work is the requirement that beyond the point of creep saturation, further increases in creep levels lead to lower coefficient of friction. This is known as negative friction, referring to the slope of the friction creep curve at saturated creep conditions. In more general tribological terms, this would be equated to changes in sliding velocity. This leads to roll-slip oscillations between the wheel and the rail which are amplified in the wheel.

The squeal noise generation is thus a non-linear process. It is therefore necessary to establish a mathematical model that will incorporate the non-linearity of the process.

Short description of the model

The lumped parameter model includes two damped single-degree-of-freedom systems (representing wheel and rail) on each side of a non-linear friction element. The system is driven to self-sustained vibrations by pulling the wheel end of the system with a constant velocity similar to the constant crabbing velocity occurring when a two-axle bogie with fixed axles is passing through a curved track. The model, shown in summarised form in figure 2.9.1, includes one mode of the wheel (shown to the left of the friction element) and one mode of the rail (shown to the right of the friction element).

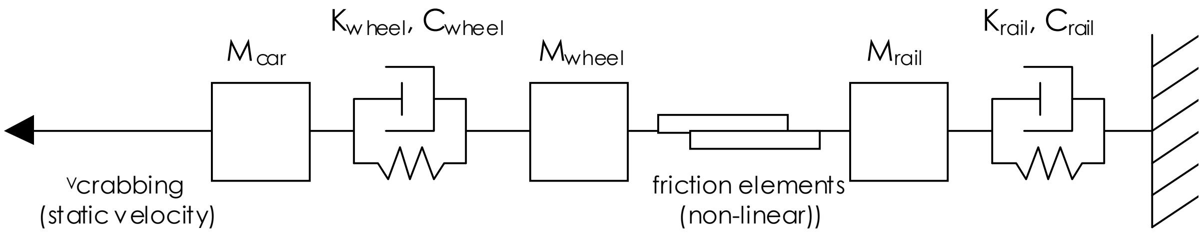


Figure 2.9.1

Conceptual sketch of the lumped parameter model for prediction of wheel/rail squeal noise

A typical non-linear friction characteristics of the contact between the wheel and the rail is stored as a (numerical) function in a finite element model and is based on measurements of actual wheel/rail friction, see figure 2.9.1.

A standard wheel/rail configuration with data according to table 2.9.1 leads to a predicted vibration velocity in the wheel according to figure 2.9.2.

Parameter	Value
Loss factor, wheel	0.004
Loss factor, rail	0.035
Resonance frequency, wheel	670 Hz
Resonance frequency, rail	400 Hz
Dynamic mass, wheel	80 kg
Dynamic mass, rail	125 kg
Vehicle velocity	7 m/s
Axle distance	2 m
Curve radius	100 m

Table 2.9.1

Data for the standard parameters case

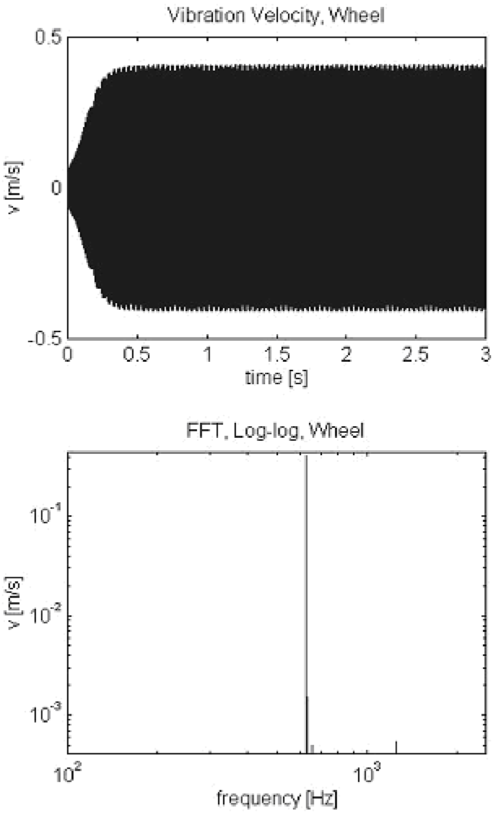


Figure 2.9.2

Wheel disc vibration velocity during squeal for a standard wheel/rail configuration shown as time history and frequency spectrum

2.9.3 Discussion

As indicated, squeal noise comes from the excitation of the first (and sometimes second) resonance of the wheel.

Apart from eliminating the origin of squeal (§2.10), the reduction or elimination of the wheel resonance is the other method. Different methods exist: resilient wheel, constrained layer damped wheels, wheel isolation absorbers.

Squeal noise never has received much attention in global noise modelling because it is only a local effect, thus not or little influencing global noise modelling. But this is not the case in urban tracks, where tram and metro curves are often frequently present in certain areas.

In the recent research project IMAGINE, therefore squeal noise has been included, although only from an arbitrary point of view. As its approach is independent of the mitigation measures, its discussion could be done in either §2.9 or §2.10.

Here, we refer to §2.10.

2.10 CURVE NOISE BY TRACKWORK LUBRICATION

Reference to D6.2: LC-Rail -5/6/7/8

2.10.1 Discussion

Trackwork lubrication is one of the most promising approaches for the reduction of squeal noise.

Wheel squeal is the most common form of curving noise, caused by stick-slip oscillation during lateral slip of the tread over the railhead. Wheel howl at curves may be related to oscillation at the wheel's lateral resonance on the axle, caused by lateral slip or flange/rail contact during curving. At short radius curves where train speeds may be limited to 20 km/h, rolling noise may be insignificant relative to wheel squeal.

As of this importance, it is important that squeal noise is taken into account in noise models.

In the actual Intern Calculation method (based on the Dutch SRM II - 1996), this is not taken into account.

In the IMAGINE rail noise model, a rather rough approximation is introduced. This will be compared to actual measurements carried out in Antwerp and Brussels on test systems of on board and fixed lubrication systems.

2.10.2 Actual EU calculation method

Squeal noise is not taken into account. It is not even mentioned.

2.10.3 IMAGINE railway noise source model

Curve squeal is a special source that is only relevant for curves and points and is therefore localised. As it can be significant, an appropriate description is required. Curve squeal is generally dependent on curvature, friction conditions, train speed and track-wheel geometry and dynamics. As all these parameters are rather complex to include in a traffic noise prediction model, it is proposed to use noise levels measured during the transit time of a vehicle squealing in a curve. This should then be corrected for the percentage of pass-bys it is expected to occur, as a default 50%, which reduces the level by 3 dB. This takes all statistical effects into account such as variation in geometry, friction, and humidity. The statistical variations over the length of the vehicle are accounted for by using the equivalent noise level measured over the pass-by length. The emission level to be used should be determined for curves with radius below 1000m and for sharper curves and branch-outs of points with radii below 100m. The noise emission should be specific to each type of rolling stock, as certain wheel types may be significantly less prone to squeal than others. The emission level $_{Lp,i,squeal}$ is given as a function of speed and curve radius, depending on the track (curve or points) and the vehicle type. The source height is at axle height (0.5m).

Squeal noise levels for different speeds or curve radii will be approximated by the following relationship:

$$L_{p,squeal,\,i} = L_{p,squeal,i}(v_0,R_0) + 20\ \lg\ (v/v_0) - 20\ \lg\ (R/R_0)$$

This formula may be used for deriving squeal noise levels at other speeds or radii, but preferably by no more than a factor 10 in speed or radius.

Default parameters for squeal noise are defined as:

$L_{p,curve\ squeal,\ points,i}$ = 100 dB @ 1 kHz, 2 kHz
for v 40 km/h and
R 40 m

$L_{p,curve\ squeal,\ curve,i}$ = 95 dB @ 2 kHz, 4 kHz
for v 80 km/h and
R 250 m

This information is a first approach to integrate squeal noise into global noise model, but retains relatively vague.

No information is given on the duration of the noise, or translation to the $L_{Aeq,1h}$.

Only one additional indication is given: 50% of the vehicles.

Therefore, this modelling is compared to actual measurements on short curves in Brussels and Antwerp.

2.10.4 Evaluation

Application and experience has been sought within the QCITY project for fixed and for on-board lubrication: WP5.3. Detailed results can be found in D5-03.

In this paragraph, only the results of the measurements with regard towards the IMAGINE Railway Noise model and more in general concerning EV Noise Mapping.

Antwerp – on-board lubrication

vehicle length:	25 m;
radius:	18 m;
measurement distance	7.5 m;
vehicle speed:	10 km/h (2.78 m/s);
L_{Amax}	96 - 99 dB(A)
L_{Aeq} (24 s)	88 – 90 dB(A)
f_{res}	1250 Hz;
see figure 2.10.1	

Following acoustical values can be calculated (figure 2.10.2):

- SEL 102 – 104 dB(A)
- T_p (duration of pass-by) 9.0 s

- TEL 92.5 – 94.5 dB(A).

Further information that can be recalled for the QCITY report:

- after only one lubrication cycle, the squeal noise was completely eliminated and did not return in the next 8 passages;
- reduction of L_{max} was 15 dB, from 99 to 84 dB(A); the L_{Aeq} noise reduction was 12 dB. This means that the squeal noise was present during 50% of the pass-by time.
- the squeal noise did contain only one frequency, the second resonance frequency (2250 Hz) was at least 15 dB lower and thus neglectable.

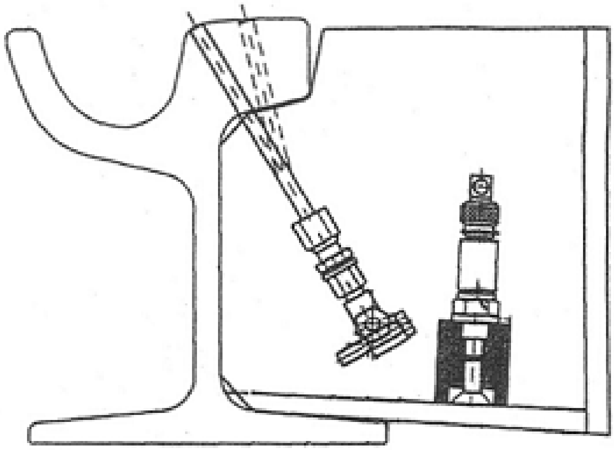


Figure 2.10.1

Conceptual design of the lubrication system

DE LIJN 10/08/2007

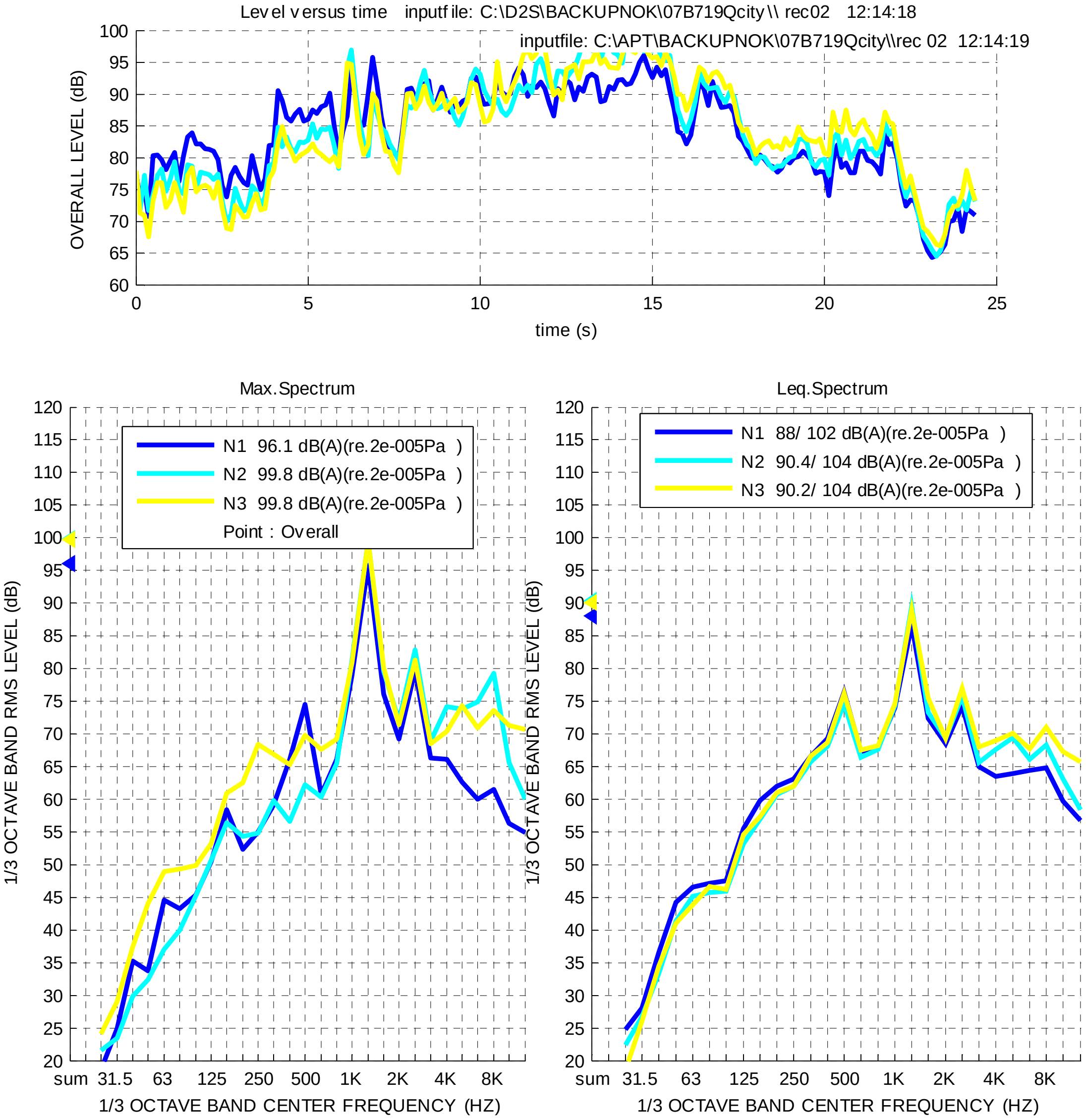


Figure 2.10.2

Brussels – fixed system

The system consists in applying before the entry in curve a lubricant in the contact zone between the wheel and the rail, thus lining the forces of friction generation wheel/rail contact noise. The application of the lubricant is done by boring holes in the root of the rail and installing a system of pipes, a pump and a tank.

For these curves, the radius was ±2.5 m.

Three types of trams did pass-by, yielding different amplitudes and resonant frequencies.

	tram	lubrication			frequency
		none	1 per 2 days	1 per day	
Lmax	T2000	91.2	84.3	77.8	800 (1600)
	T3000	89.6	73.1	73.6	1000
	T4000	86.9	77.9	74.7	1000 (2000)
TEL	T2000	86.0	80.3	75.3	
	T3000	83.5	73.1	72.3	
	T4000	81.8	75.2	73.5	

Table 2.10.1

Out of these measurements, we observe:

- squeal noise leads to an increase of 14 – 16 dB(A) on L_{Amax} and 10 – 12 dB(A) on TEL.
- squeal noise is present during 1/3 of the pass-by;
- for the noisier vehicles, also the second resonance is (slightly) present in the spectrum;
- for the more sensitive vehicles, more lubrication is needed to avoid/eliminate completely squeal.

IMAGINE Rail Source Model (IRSM)

For tram vehicles, it can be seen that the IRSM model overestimates squeal:

- normally, one resonance per frequency is present;
- a TEL level of 95 dB(A) should be sufficient.

On the other hand, it has been proven that if squeal is present, it largely dominates all other railway sources, and this definitely at low speeds.

2.10.5 EU Noise mapping

Squeal noise is mostly a local complaint. Therefore, its use in a city noise action plan is limited. This is illustrated hereafter for a city area in Brussels.

On the other hand, squeal noise is a real problem in cities: the noise level is very high and the nuisance is important.

This was again confirmed by the municipality of Brussels. During the above test, the system broke down twice. Each time, before technical inspection identified the problem, the city already has received noise complaints.

To simulate suppression of squeal noise, the augmentation of the emission level in the curve was removed. Then, calculation of L_{den}, L_{night} and number of annoyed was carried out. Again sensibility towards a global (or a local) approach is looked for, figure 2.10.3, table 2.10.3.

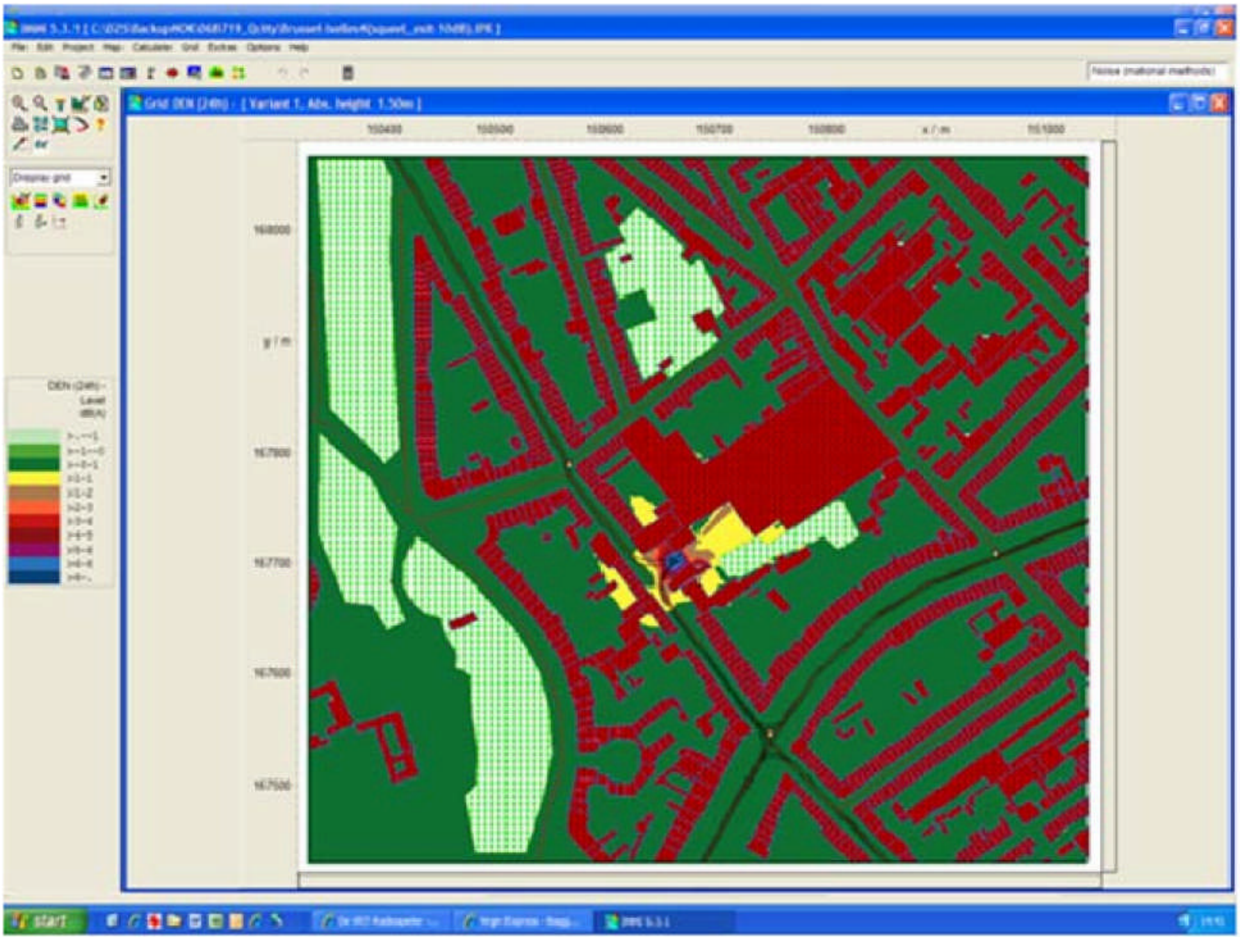


Figure 2.10.3

	Inhabitants of a building with a value at the most exposed façades inside the specified range	
	Original	Δ when elimination of squeal noise
Road & Rail		
… < L_{den} < 55 dB	1092	0
55 ≤ L_{den} < 60 dB	233	0
60 ≤ L_{den} < 65 dB	1572	0
65 ≤ L_{den} < 70 dB	885	0
70 ≤ L_{den} < 75 dB	625	0
75 ≤ L_{den} < …	1977	0
sum	6381	0
Rail only		
… < L_{den} < 55 dB	4337	0
55 ≤ L_{den} < 60 dB	574	81
60 ≤ L_{den} < 65 dB	526	76
65 ≤ L_{den} < 70 dB	887	-97
70 ≤ L_{den} < 75 dB	39	-39
75 ≤ L_{den} < …	21	21
sum	6384	0

Table 2.10.2

There it can be observed that inside a global map, the information is completely lost, no influence on L_{den} or L_{night}. But, on a local scale, rail transport, a few hundred people are considered.

2.11 TURNOUTS (RAIL SWITCHES)

Reference to D6.2: LC-Rail -10/11/12

Many noise hot-spots and noise complaints in cities relate to areas where special trackwork (crossings, turnouts, …) is installed.

For hot-spot analysis, special trackwork is taking into account with an increase of L_{max} by 10 dB(A) at trackwork locations. Measurement campaigns carried out in Ghent and Antwerp on twelve different turnouts (same vehicle, same speed) varies between 3 and 22 dB(A) (L_{max} value).

For European strategic noise mapping, the Dutch SRM II method proposes an identical approach between rail joints (gaps) and switches. This is correct, because in each case, the noise is created by the impact of the wheel falling into the gap.

This has been discussed in detail in §2.7 of the present report, and thus will not be repeated here.

In this discussion, it has been concluded that although a clear link has been indicated between the height of the impact (equivalent wheel flat), this parameter does not appear in the actual modelling methods. These methods limit themselves to an average value over a 100 m area in which a switch, or cross-over appears.

2.12 STEEL BRIDGES

Reference to D6.2: LC-Rail -13/14/15/16

2.12.1 Discussion (see also D3.9)

On a normal ballasted track, sound is mainly radiated by the rails, sleepers and the wheels of the train, originating from the roughness of wheels and rail. On a steel bridge, the train also induces vibrations in the bridge itself. These structure born vibrations radiate noise, which is generally louder (5-15 dB) than the rolling noise itself.

To reduce structural noise when a train passes over a steel bridge, one can:

- prevent the excitation of the bridge structure by:
  - moving special trackwork away from bridges (LC-Rail 13);
  - isolation of the bridge structure from rail vibrations: vibration isolation of rail (LC-Rail 14);
  - make bridge structure less sensitive for excitation;
- absorb the bridge vibration by dissipation of vibrations by damping:
  - bridge (tuned) vibration damper(LC-Rail 15);
  - plate damping (LC-Rail 16).

Several examples are known and presented (see D3.9), combining several of the above mitigation measures yielding improvements of approximatively 8 dB.

Actually no validated calculation methods are available. The frequency range for the structure born noise is between 40 and 200 Hz. In this frequency range and for this type of large structure, finite element calculations are valid for lower frequencies but imprecise at those frequencies because the modal density is already too high. Statistical Energy Analysis such as used for TWINS or WR-Noise Model is not reliable at frequencies below 300 Hz. Measurement of vibrational and/or acoustical transfer functions in the situation of refurbishing are the most reliable approach.

2.12.2 Actual Modelling (SRM II -1996)

For concrete structures, no specific additional radiation aspects have to be defined.

For steel constructions and the track type constructions installed thereupon, the emission is contained in the corresponding correction factor for tracks as a result of the rolling noise. Sound emissions from the construction itself are incorporated into the final emission level by raising the emission factor E by $\Delta L_{E.bridge}$ i.e. the additional calculation *extra charge* for bridges.

As a result, the effectiveness of screens mounted on the constructions is highly overestimated. The reliability, as far as calculating screens on steel constructions is concerned, is therefore questionable.

In the case of a bridge with screens, the additional correction must be determined by measurement.

2.12.3 Future Modelling (IMAGINE: D12/13)

Only following recommendation is given for measurement of bridge noise: "*For bridges, the track transfer function must be determined by measurement or calculation in the same way as done for the track.*"

No equation for bridge noise modelling is given.

No default value for bridge noise supplement is given.

2.12.4 Discussion

All existing and future calculation methods come down to a bridge noise supplement. As all calculation methods use octave or 1/3 octave bands, it seems more logical to express the bridge noise supplement accordingly.

Although all bridges are different, analysis of existing literature and tests permits to deduct following general approach.

A classical steel bridge gives an increase of 6 dB(A). This is due to low frequency structure born noise (approximatively 10 dB) and increased radiation of rolling noise (approximatively 3 dB).

Following spectrum can be proposed (bridge increase):

frequency	63	125	250	500	1000	2000	4000	Hz
increase	10	10	10	6	3	3	3	dB

Different mitigation measures then can be evaluated towards the above spectrum:

- low frequency vibration isolation (f_n: 25 Hz);
- rail/plate damping (high frequency, f_n: 125 Hz));
- radiation reduction (global frequency).

Following mitigation spectra are proposed:

frequency	63	125	250	500	1000	2000	4000	Hz
low frequency	-4	-7	-5	-3	-1	-1	-1	dB
rail/plate damping	0	0	-3	-6	-3	-3	-3	dB
global frequency reduction	-4	-7	-10	-6	-3	-3	-3	dB

2.12.5 Evaluation (Ostend)

This project is recalled from WP1.1 (D1.2): a combined model for train (container train in harbour), tramways and road at the end of a harbour area. Both tramways and train were passing each over a steel bridge.

The original study indicated that road traffic annoyance is dominant. Train/tram noise was only local (L_{night}):

- train: 106/1666;
- tram: 367/1666.

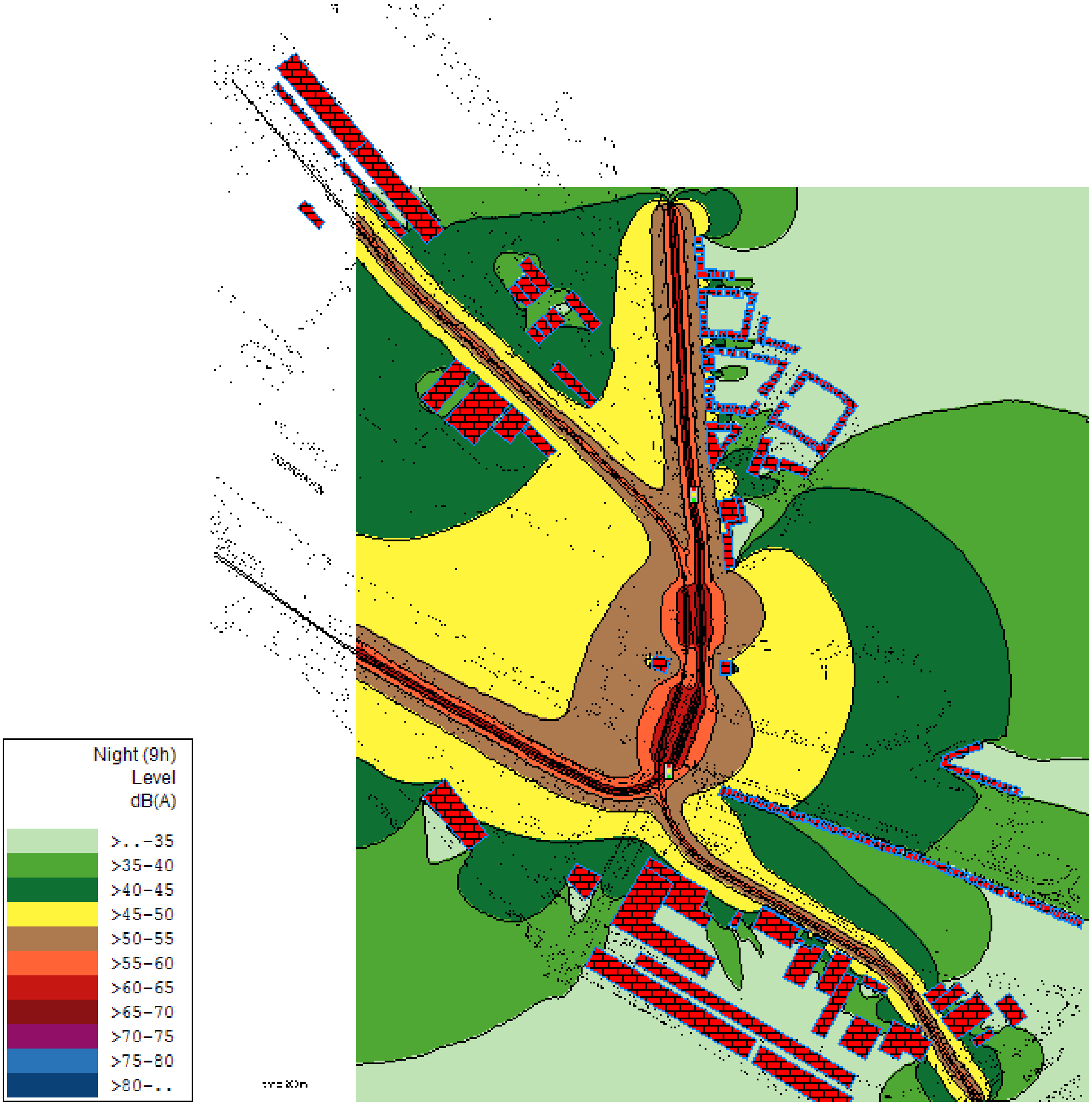


Figure 2.12.1

Train & tram noise maps

Proposal of different mitigation measures are studied:

- high frequency vibration isolation by rail damper or rail pads (f_n: 125 Hz);
- low frequency isolation of track (f_n: 25 Hz).

Differentiation maps are calculated separately for train and tram.

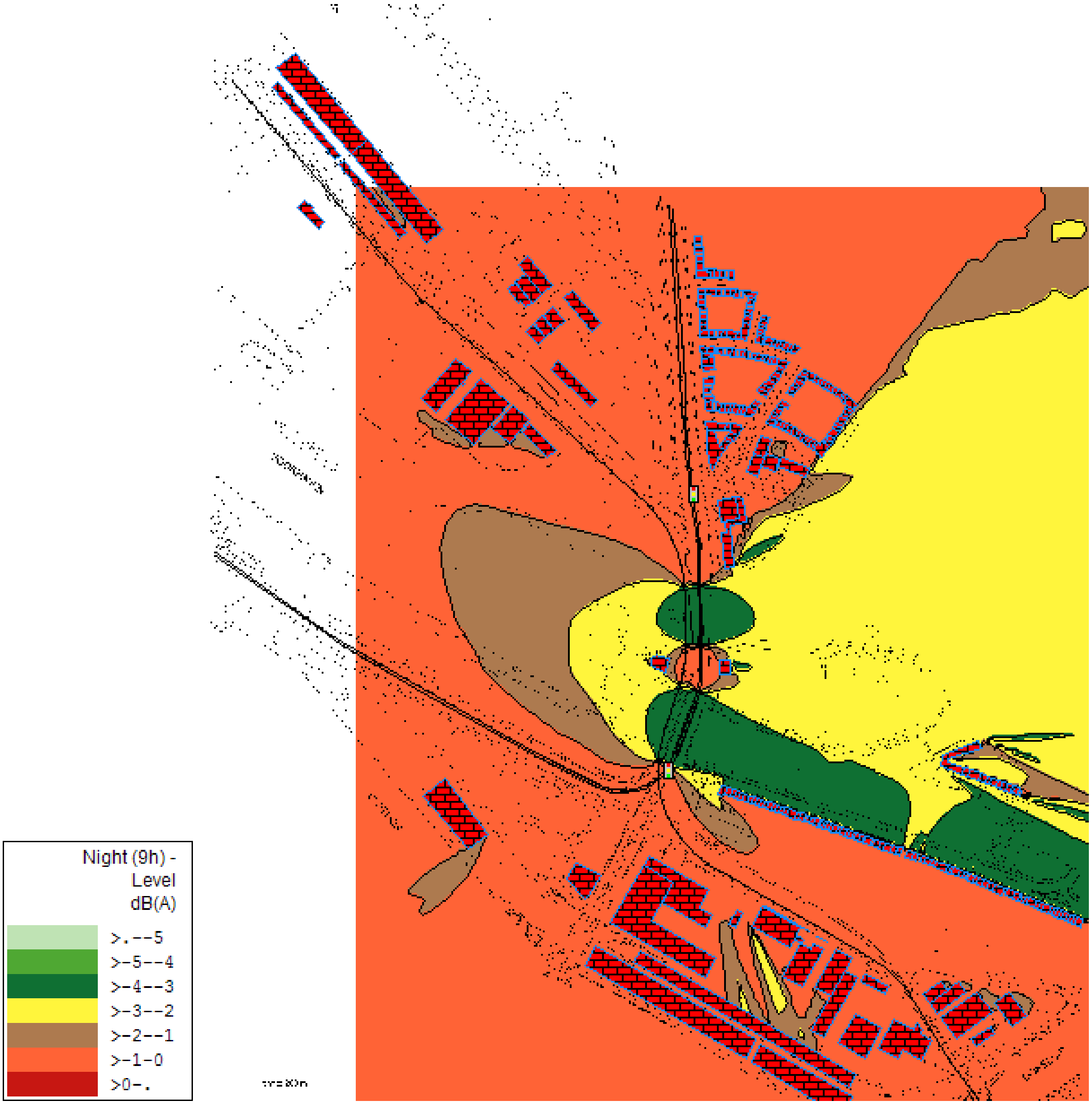


Figure 2.12.2

Train - Grinding high frequency – improvement in ΔdB

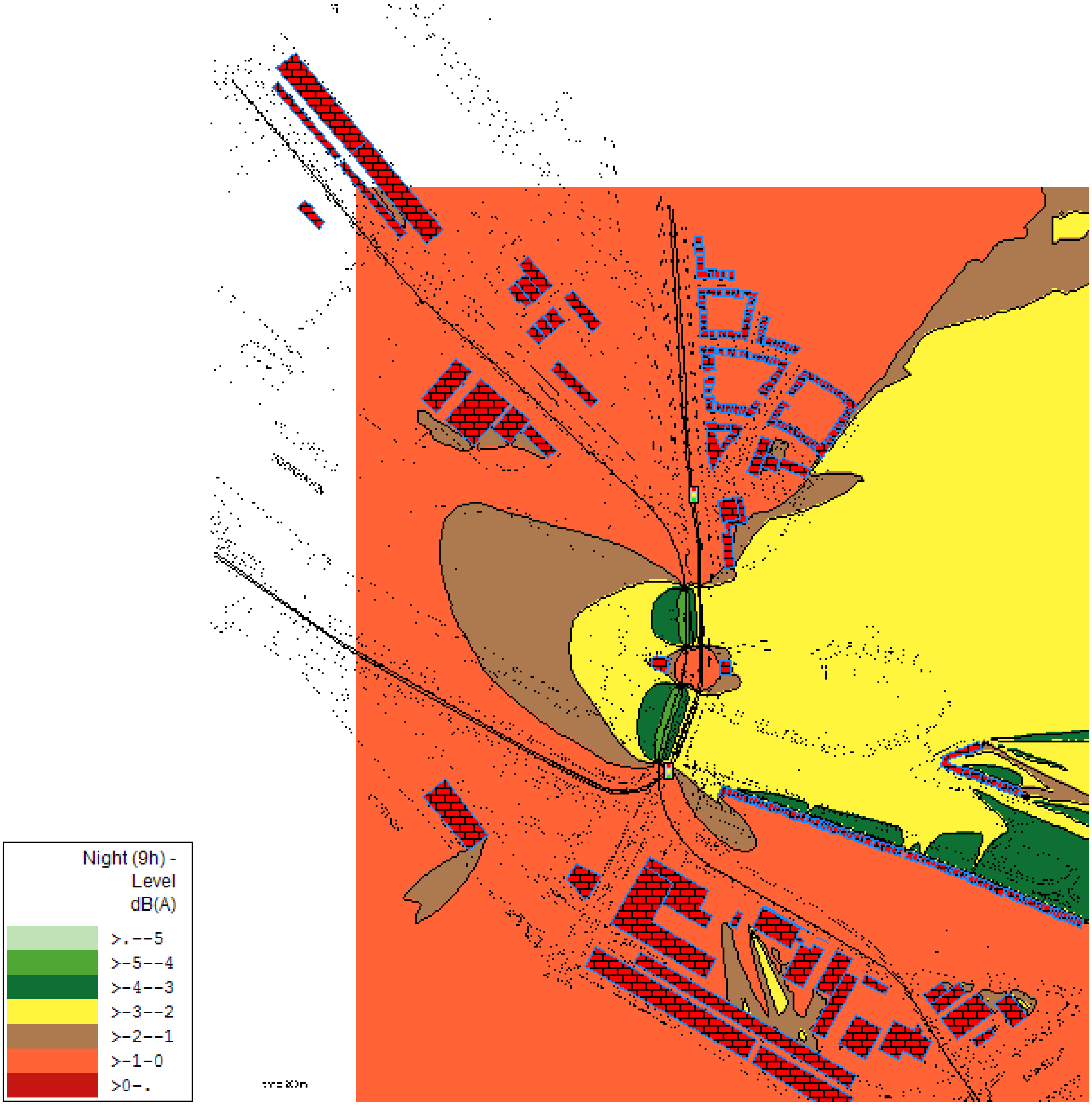


Figure 2.12.3

Tram - Grinding low frequency – improvement in ΔdB

Difference is also calculated as function of number of annoyed.

		Ref	Low Freq Isolation	High Freq Isolation	Global Isolation
Variant: Noise index	Train Range /dB				
DEN (24h)	... < Lden < 55 dB	1639	1666	1639	1666
	55 <= Lden < 60 dB	27	0	27	0
	60 <= Lden < 65 dB	0	0	0	0
	65 <= Lden < 70 dB	0	0	0	0
	70 <= Lden < 75 dB	0	0	0	0
	75 <= Lden <... dB	0	0	0	0
	Sum	1666	1666	1666	1666
Night (9h)	... < Ln < 45 dB	1560	1639	1628	1639
	45 <= Ln < 50 dB	79	27	38	27
	50 <= Ln < 55 dB	27	0	0	0
	55 <= Ln < 60 dB	0	0	0	0
	60 <= Ln < 65 dB	0	0	0	0
	65 <= Ln < 70 dB	0	0	0	0
	70 <= Ln <... dB	0	0	0	0
	Sum	1666	1666	1666	1666
Variant: Noise index	Tram Range /dB				
DEN (24h)	... < Lden < 55 dB	1304	1317	1325	1325
	55 <= Lden < 60 dB	57	44	96	96
	60 <= Lden < 65 dB	305	305	245	245
	65 <= Lden < 70 dB	0	0	0	0
	70 <= Lden < 75 dB	0	0	0	0
	75 <= Lden <... dB	0	0	0	0
	Sum	1666	1666	1666	1666
Night (9h)	... < Ln < 45 dB	1257	1295	1295	1299
	45 <= Ln < 50 dB	77	39	39	35
	50 <= Ln < 55 dB	332	332	332	332
	55 <= Ln < 60 dB	0	0	0	0
	60 <= Ln < 65 dB	0	0	0	0
	65 <= Ln < 70 dB	0	0	0	0
	70 <= Ln <... dB	0	0	0	0
	Sum	1666	1666	1666	1666

Table 2.12.1

In the table, some interesting results are observed:

- low frequency isolation is more effective for train noise, and is sufficient to get all $L_{night} < 50$ dB;
- high frequency isolation is more effective for tram noise; additional low frequency isolation does not give any further improvement.

Noise rating model

To be done.

2.12.6 Conclusion

Evaluation of bridge noise and its mitigation measures needs a spectral approach. Different mitigation measures can be evaluated and optimal solutions may differ from one noise source to another.

3 ROAD TRAFFIC

3.1 INTRODUCTION

To realise the different measures for road traffic (tyre/road interaction), one have to understand the different mechanisms that contribute to the overall sound level from the tyre/road interaction. The noise from road traffic can be divided into two types; tyre/road interaction and engine/transmission noise. The two sources contribute with different amount at different speeds.

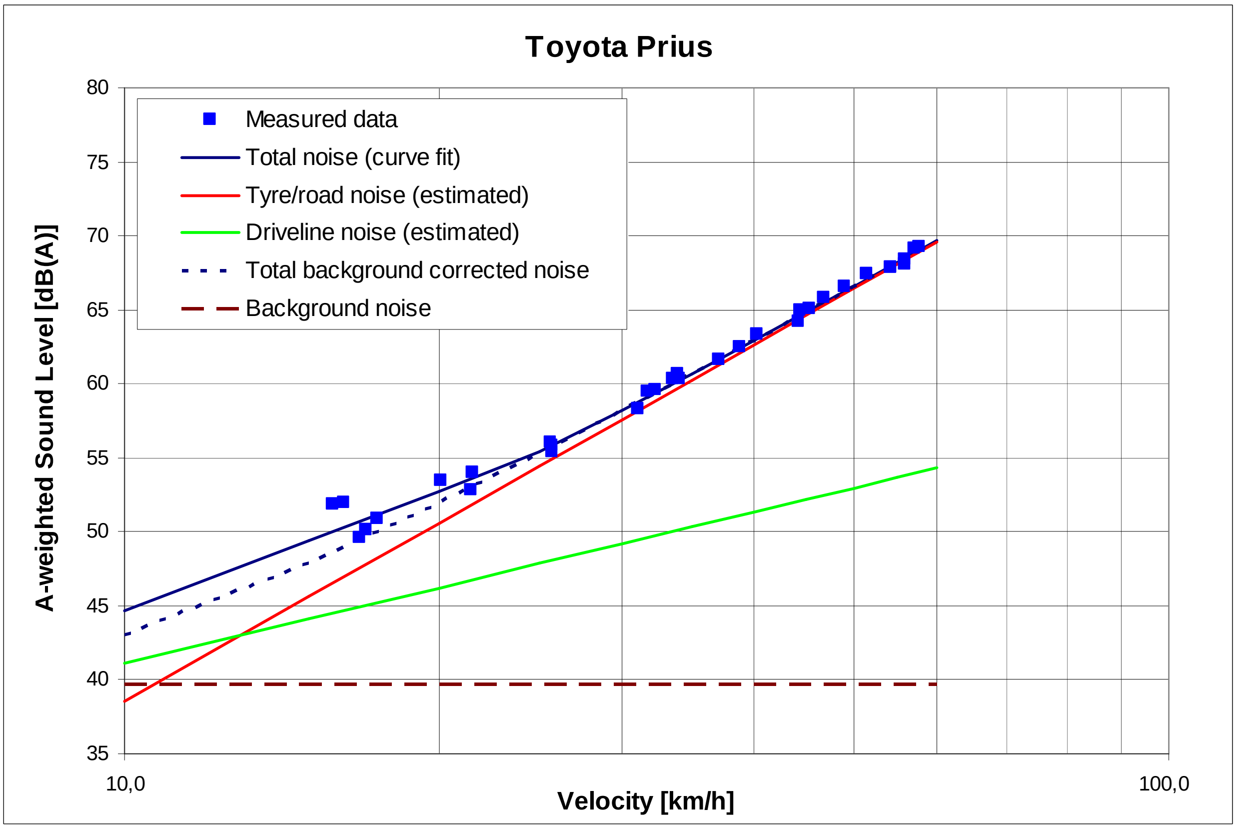


Figure 3.1

Measurement of tyre/road noise as well as engine/transmission noise for a petrol/electrical hybrid car (Toyota Prius).

Measures applied to these two main sources can be implemented to a certain extent in the Nordic Prediction model. The QCity project focuses on the tyre/road interaction and therefore the implementation of these measures in the Nordic Prediction model will be discussed.

The noise generated from the tyre/road interaction is dependent on both the tyre and the road surface. Quiet tyre designs, and road surfaces alone can only do so much but combined the can make great improvement to the noise emitted by passing vehicles.

We chose to show how the different effects can be implemented in the Nordic Prediction model using two of the leading noise calculation software used today; CadnaA and SoundPLAN.

Horn effect

The tyre and road surface form a horn triangular cavity resembling a horn. This amplifies the noise created when the thread blocks make contact with the road surface. Due to the nature of the horn this effect becomes greater with increasing tyre width. To reduce noise from this effect the tyre can be made thinner or the tyre design changed to resemble a dual tyre. More information can be found in D3.23.

Tyre thread pattern

To allow vehicles to perform in many different conditions of everyday use road vehicle tyres have different thread patterns. These can be designed to give enhanced grip in wet conditions or be optimized for tight bends in high speeds. The pattern design, also have a impact on the noise emitted from the tyre road interaction. Most tyre manufactures have “quiet” tyres on their list today. A quiet thread pattern combined with reduced horn effect can reduce rolling noise with up to 6-8 dB.

Road surface roughness

Road roughness induced tyre/road noise is proportional to:

$$L_{ROAD} \sim C + 10\log d$$

d	maximum stone size in the asphalt road mix.
C	arbitrary constant dependent on measurement distance, speed, etc.

As an example. If the maximum stone size is changed from 16mm (d1) to 8mm (d2) the resulting noise reduction will roughly be D=10log(d1/d2)=3dB. In effect, a smooth road surface with small maximum stone size will be less noisy than a road surface with a larger maximum stone size.

Road surface porosity

By making the road surface porous, the surface itself can work as an absorbent. This way of reducing tyre/road noise has been tested with great success in Stockholm as well as in Gothenburg.

Road surface elasticity

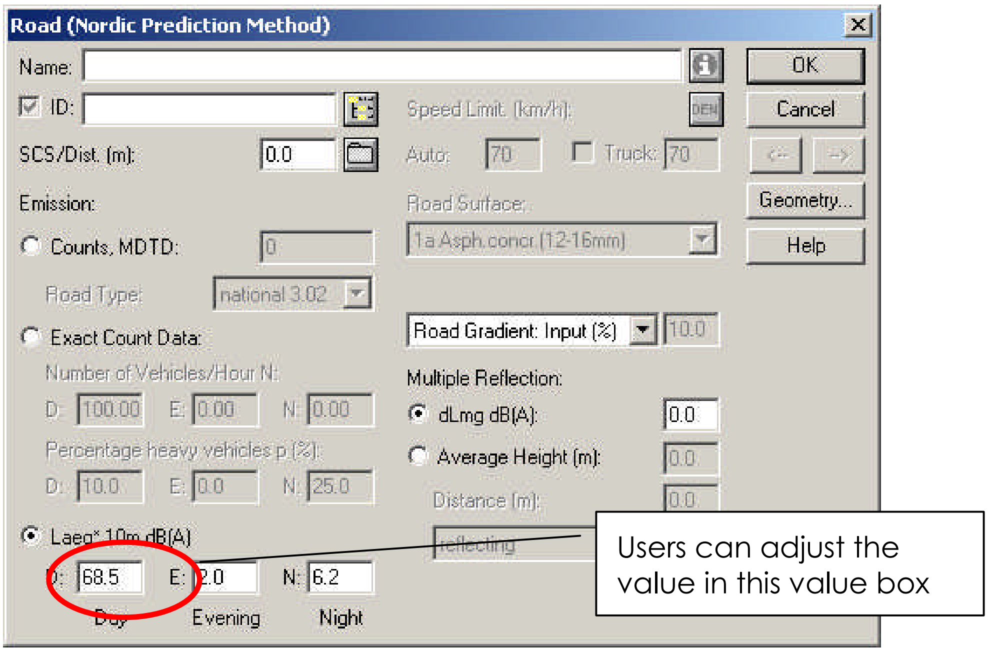
If the impedance of the road surface is changed in a way to make it resemble the impedance of the tyre rolling on it, the generated noise can be reduced. The reduction using this method is in the order of 1-2 dB.

3.2 TYRE DESIGN

Tyres can be designed to be less noisy. To cope with the horn effect tyres can be "thinner" and less noisy thread patterns are constantly being developed.

Including quiet tyres in the Nordic Prediction model is made by separating the number of vehicles using quiet tyres from the rest. Two calculations can then be made, one for each type of tyre. Then a correction can be made to the calculation that includes the quiet tyres and by combining the two calculations the resulting noise map is derived. If the percentage of vehicles equipped with quiet tyres is known and is constant over the area chosen for calculation, a mean correction can be applied to a calculation of sound levels from all cars.

This procedure can be made using any of the two above mentioned calculation programs.



Road (Nordic Prediction Method)

Name:

☑ ID:

SCS/Dist. (m): 0.0

Emission:

○ Counts, MDTD: 0

Road Type: national 3.02

○ Exact Count Data:

Number of Vehicles/Hour N:

D: 100.00 E: 0.00 N: 0.00

Percentage heavy vehicles p (%):

D: 10.0 E: 0.0 N: 25.0

● Laeq* 10m dB(A)

D: 68.5 E: 2.0 N: 6.2

Day Evening Night

Speed Limit (km/h):

Auto: 70 ☐ Truck: 70

Road Surface: 1a Asph.concr.(12-16mm)

Road Gradient: Input (%) 10.0

Multiple Reflection:

● dLmg dB(A): 0.0

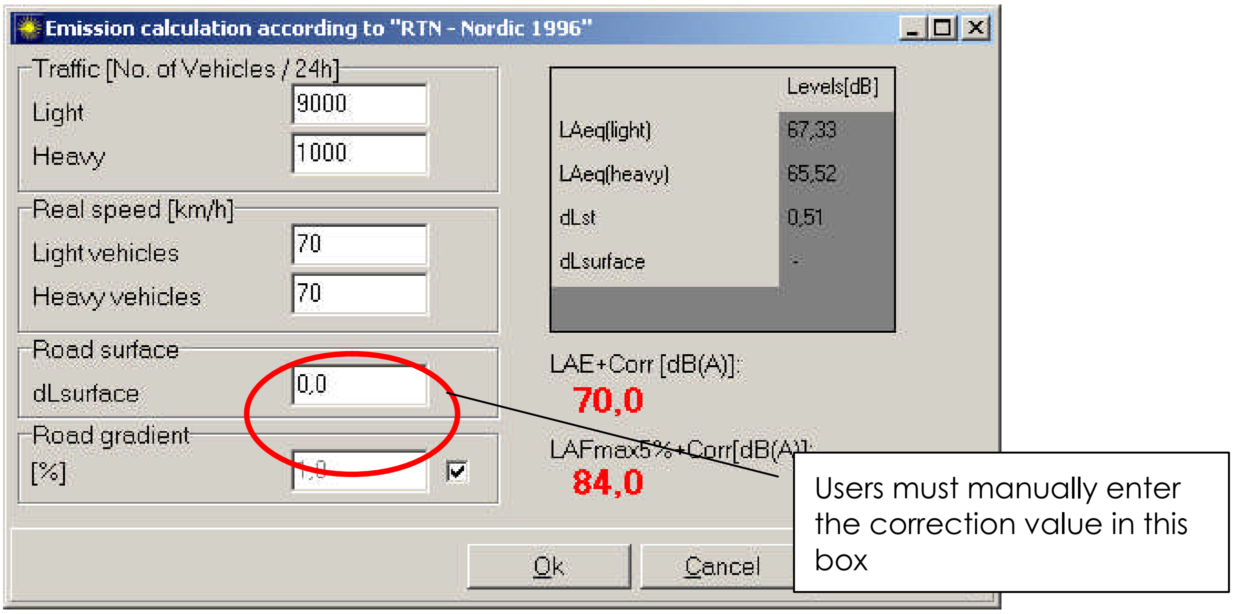
○ Average Height (m): 0.0

Distance (m): 0.0

reflecting

Users can adjust the value in this value box

Figure 3.2 The road options window i CadnaA



Emission calculation according to "RTN - Nordic 1996"

Traffic [No. of Vehicles / 24h]
Light: 9000
Heavy: 1000

Real speed [km/h]
Light vehicles: 70
Heavy vehicles: 70

Road surface
dLsurface: 0,0

Road gradient
[%]: 1,0 ☑

	Levels[dB]
LAeq(light)	67,33
LAeq(heavy)	65,52
dLst	0,51
dLsurface	-

LAE+Corr [dB(A)]: 70,0

LAFmax5%+Corr[dB(A)]: 84,0

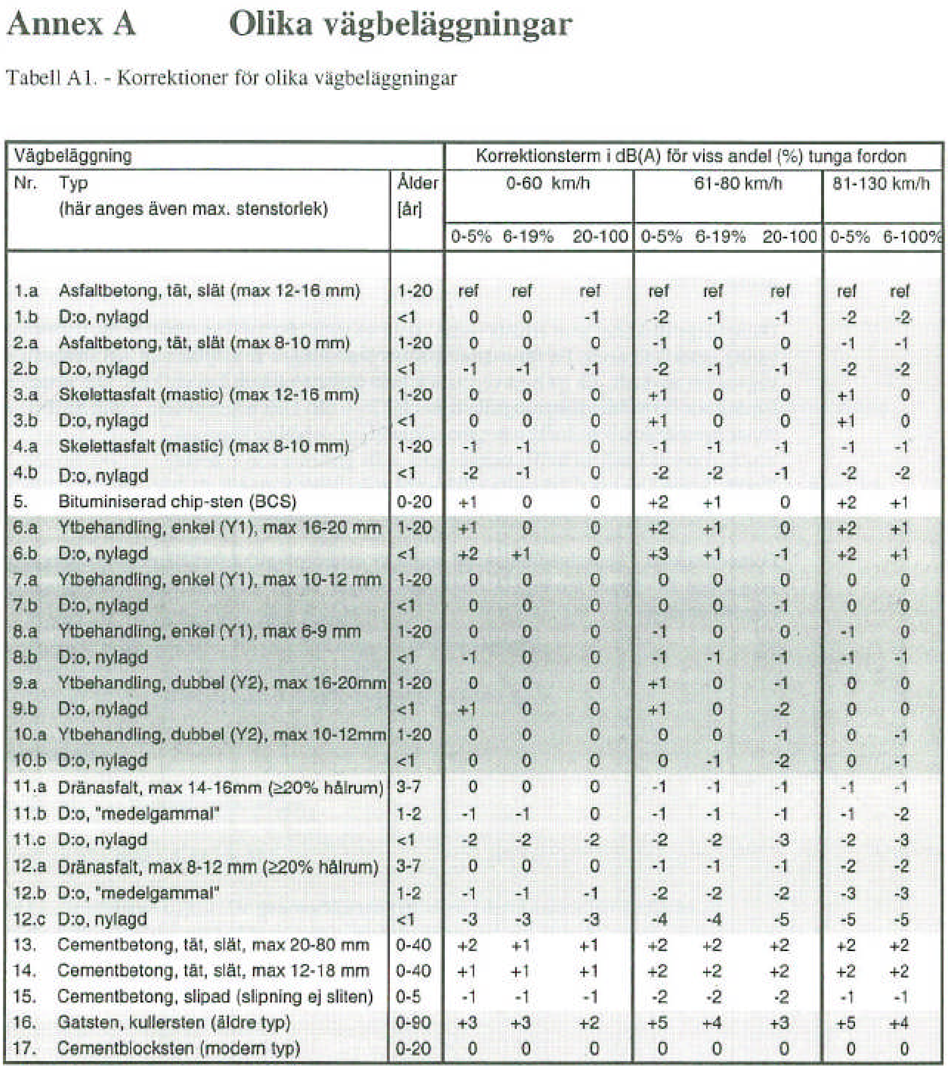
Users must manually enter the correction value in this box

Figure 3.3

The road options window i Soundplan

3.3 ROAD SURFACE

It has been known for some time that different road surfaces generate a wide range of noise when driven on. For example, a road paved with cobblestones generates more noise than a smooth or absorbing road surface. This have been implemented in the Nordic Prediction model since 1996.



Annex A Olika vägbeläggningar

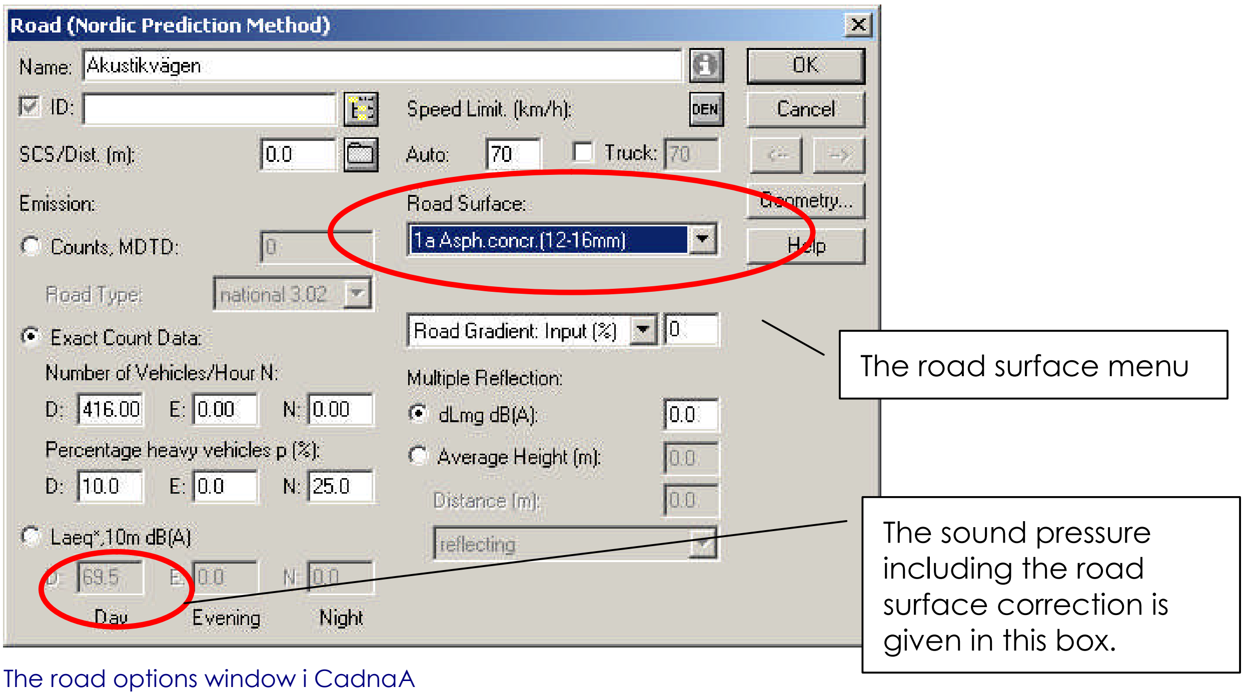
Tabell A1. - Korrektioner för olika vägbeläggningar

Vägbeläggning			Korrektionsterm i dB(A) för viss andel (%) tunga fordon							
Nr.	Typ (här anges även max. stenstorlek)	Ålder [år]	0-60 km/h			61-80 km/h			81-130 km/h	
			0-5%	6-19%	20-100	0-5%	6-19%	20-100	0-5%	6-100%
1.a	Asfaltbetong, tät, slät (max 12-16 mm)	1-20	ref	ref	ref	ref	ref	ref	ref	ref
1.b	D:o, nylagd	<1	0	0	-1	-2	-1	-1	-2	-2
2.a	Asfaltbetong, tät, slät (max 8-10 mm)	1-20	0	0	0	-1	0	0	-1	-1
2.b	D:o, nylagd	<1	-1	-1	-1	-2	-1	-1	-2	-2
3.a	Skelettasfalt (mastic) (max 12-16 mm)	1-20	0	0	0	+1	0	0	+1	0
3.b	D:o, nylagd	<1	0	0	0	+1	0	0	+1	0
4.a	Skelettasfalt (mastic) (max 8-10 mm)	1-20	-1	-1	0	-1	-1	-1	-1	-1
4.b	D:o, nylagd	<1	-2	-1	0	-2	-2	-1	-2	-2
5.	Bituminiserad chip-sten (BCS)	0-20	+1	0	0	+2	+1	0	+2	+1
6.a	Ytbehandling, enkel (Y1), max 16-20 mm	1-20	+1	0	0	+2	+1	0	+2	+1
6.b	D:o, nylagd	<1	+2	+1	0	+3	+1	-1	+2	+1
7.a	Ytbehandling, enkel (Y1), max 10-12 mm	1-20	0	0	0	0	0	0	0	0
7.b	D:o, nylagd	<1	0	0	0	0	0	-1	0	0
8.a	Ytbehandling, enkel (Y1), max 6-9 mm	1-20	0	0	0	-1	0	0	-1	0
8.b	D:o, nylagd	<1	-1	0	0	-1	-1	-1	-1	-1
9.a	Ytbehandling, dubbel (Y2), max 16-20mm	1-20	0	0	0	+1	0	-1	0	0
9.b	D:o, nylagd	<1	+1	0	0	+1	0	-2	0	0
10.a	Ytbehandling, dubbel (Y2), max 10-12mm	1-20	0	0	0	0	0	-1	0	-1
10.b	D:o, nylagd	<1	0	0	0	0	-1	-2	0	-1
11.a	Dränasfalt, max 14-16mm (≥20% hålrum)	3-7	0	0	0	-1	-1	-1	-1	-1
11.b	D:o, "medelgammal"	1-2	-1	-1	0	-1	-1	-1	-1	-2
11.c	D:o, nylagd	<1	-2	-2	-2	-2	-2	-3	-2	-3
12.a	Dränasfalt, max 8-12 mm (≥20% hålrum)	3-7	0	0	0	-1	-1	-1	-2	-2
12.b	D:o, "medelgammal"	1-2	-1	-1	-1	-2	-2	-2	-3	-3
12.c	D:o, nylagd	<1	-3	-3	-3	-4	-4	-5	-5	-5
13.	Cementbetong, tät, slät, max 20-80 mm	0-40	+2	+1	+1	+2	+2	+2	+2	+2
14.	Cementbetong, tät, slät, max 12-18 mm	0-40	+1	+1	+1	+2	+2	+2	+2	+2
15.	Cementbetong, slipad (slipning ej sliten)	0-5	-1	-1	-1	-2	-2	-2	-1	-1
16.	Gatsten, kullersten (äldre typ)	0-90	+3	+3	+2	+5	+4	+3	+5	+4
17.	Cementblocksten (modern typ)	0-20	0	0	0	0	0	0	0	0

Figure 3.4

Corrections in the Nordic Prediction model due to road surface.

CadnaA users have the possibility to change road surface in the road window menu. Datakustik has fully implemented the road surface correction table making it easier for the user. The user selects a road surface; the software will then automatically fetch the correct value.



Road (Nordic Prediction Method)

Name: Akustikvägen

☑ ID:

SCS/Dist. (m): 0.0

Speed Limit. (km/h):

Auto: 70 ☐ Truck: 70

Emission:

○ Counts, MDTD: 0

Road Type: national 3.02

● Exact Count Data:

Number of Vehicles/Hour N:

D: 416.00 E: 0.00 N: 0.00

Percentage heavy vehicles p (%):

D: 10.0 E: 0.0 N: 25.0

○ Laeq*,10m dB(A)

D: 69.5 E: 0.0 N: 0.0

Day Evening Night

Road Surface: 1a Asph.concr.(12-16mm)

Road Gradient: Input (%) 0

Multiple Reflection:

● dLmg dB(A): 0.0

○ Average Height (m): 0.0

Distance (m): 0.0

reflecting

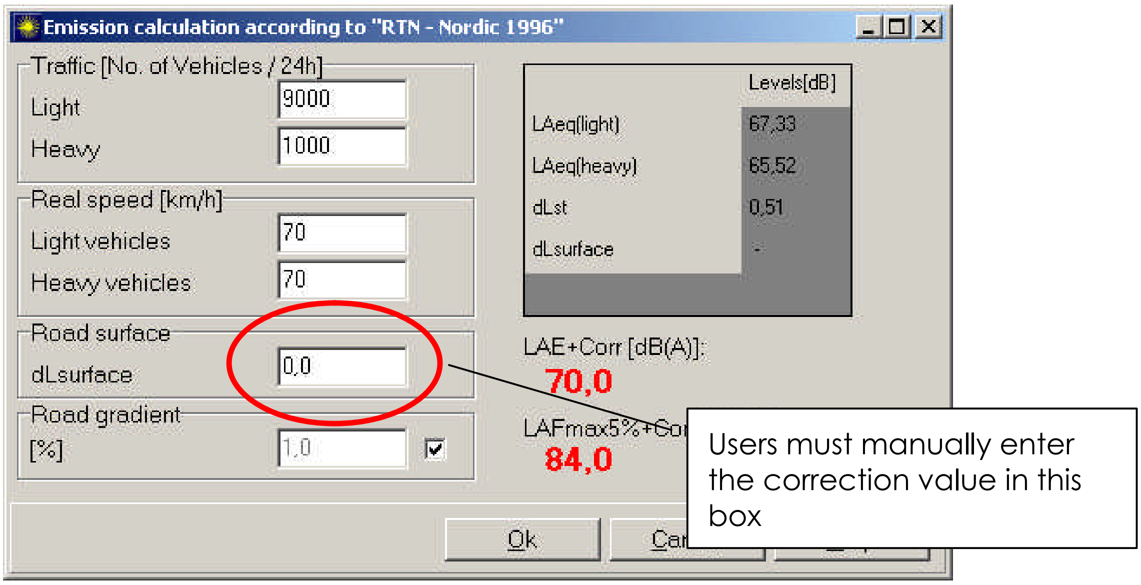
The road surface menu

The sound pressure including the road surface correction is given in this box.

Figure 3.5

The road options window i CadnaA

Braunstein + Berndt GmbH, the programmers of SoundPLAN, has not at this time implemented the road surface correction table presented in the Nordic prediction method. The user must correct this by manually enter a value which he or she must look up. This requires that the user has access to the road surface correction table.



Emission calculation according to "RTN - Nordic 1996"

Traffic [No. of Vehicles / 24h]

Light 9000

Heavy 1000

Real speed [km/h]

Light vehicles 70

Heavy vehicles 70

Road surface

dLsurface 0,0

Road gradient

[%] 1,0 ☑

	Levels[dB]
LAeq(light)	67,33
LAeq(heavy)	65,52
dLst	0,51
dLsurface	-

LAE+Corr [dB(A)]: 70,0

LAFmax5%+Cor 84,0

Users must manually enter the correction value in this box

Figure 3.6

The road options window in SoundPLAN.

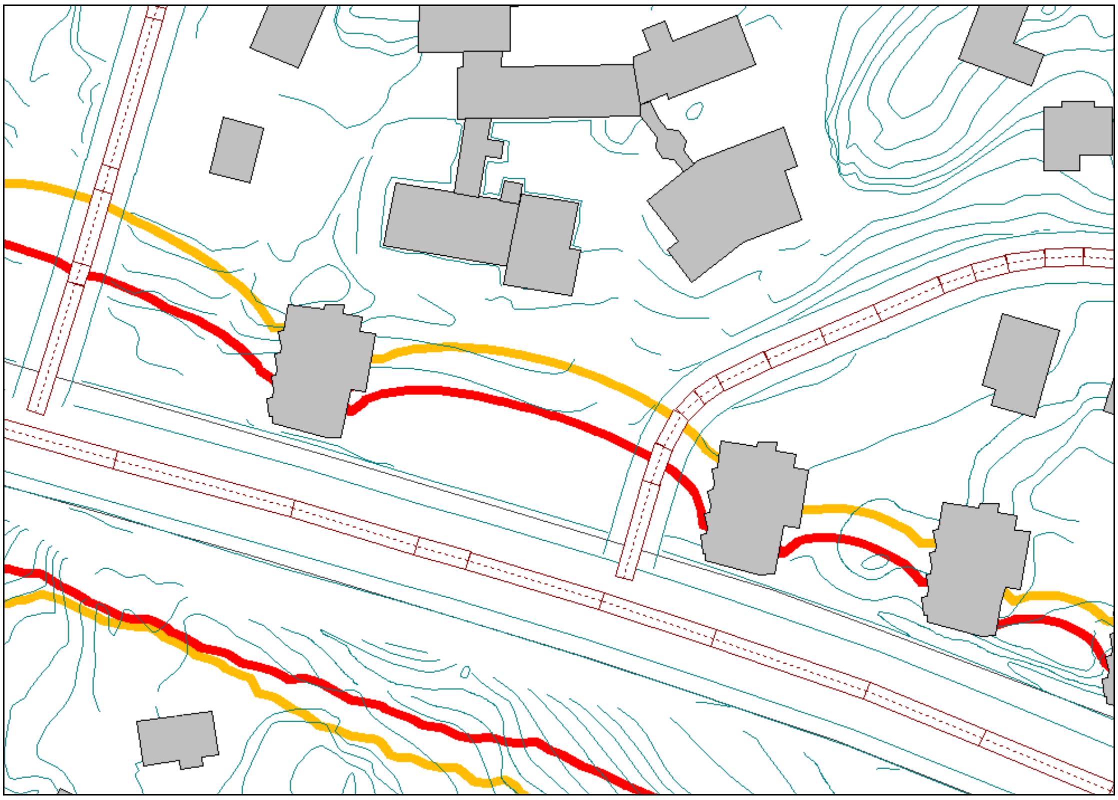


Figure 3.7

Picture showing the calculated 55 dB(A)-line for newly paved Asphalt concrete 12-16 mm (red) and after it has aged a year (orange). Calculated using CadnaA.