

3 DESCRIPTION OF MAIN S & T RESULTS/FOREGROUNDS

3.1 Rolling noise modelling

Within Quiet-Track a standard wheel rail noise simulation model and software called WRNOISE has been used and extended to include curving noise and low frequency noise (WP2).

3.1.1 Rolling noise emission model for curving conditions

A new development in the existing program WRNOISE is integrated to numerically predict the pass-by rolling noise in curves.

Considering the second contact patch at the rail gauge corner, the influence of the flange contact was added to the vehicle/track interaction formulation by adding the lateral wheel/rail roughness. For each contact point, contact patch filter and a roughness profile are introduced.

Taking into account the geometry of the track in a curve, the normal and lateral forces are first determined. After redistribution of the normal loads, two cases are possible: (1) one contact point and (2) double contact points at the high rail. To better understand the redistribution of normal load and their associated contact patches in the curves, the vehicle on a curved track is numerically analysis by means of a dynamic multi-body simulation software (VI-Rail) in which a vehicle with two wheel sets is running at constant speed on a track including a tangent segment and subsequently a curved segment.

Main result

In the QUIET-TRACK project, a methodology was proposed to account for the effect of the curves in the pass-by noise. Considering the second contact patch at the rail gauge corner (in curves), the influence of the flange contact was added to the vehicle/track interaction formulation by adding the lateral wheel/rail roughness. For each contact point, then, a contact patch filter and a roughness profile are introduced.

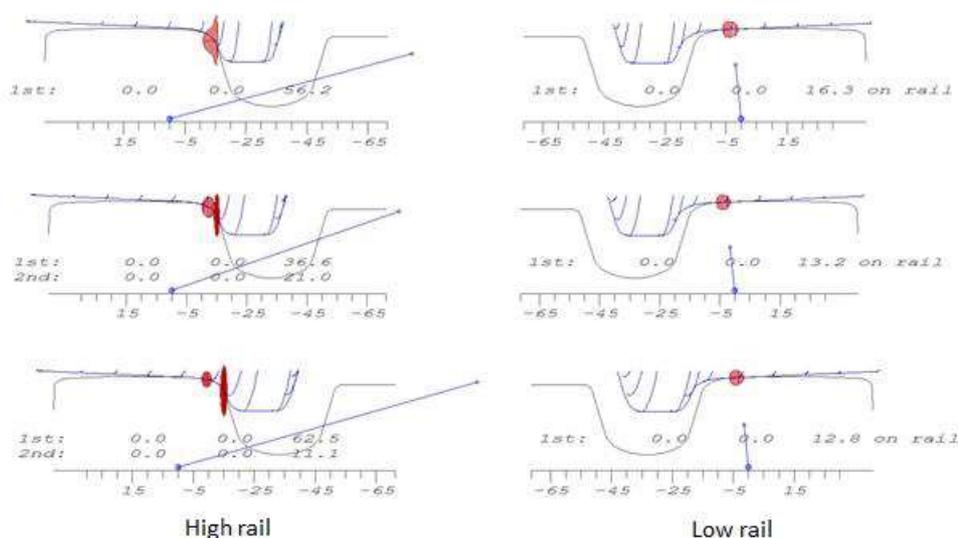


Figure 1: Changing contact conditions during curving (VI Rail)



New features including “2D roughness” and “double contact points” have been integrated within the WRNOISE program.

A numerical study has been performed to show the effect of the curved track on generated rolling noise. Considering a new distribution for the axle load as well as the lateral roughness, the results of the numerical modelling shows an increase of 2-7 dB in the pass-by noise in the curved track compared with a tangent track. A similar field result has been found by measurements in the network of Infrabel in Mons (Belgium).

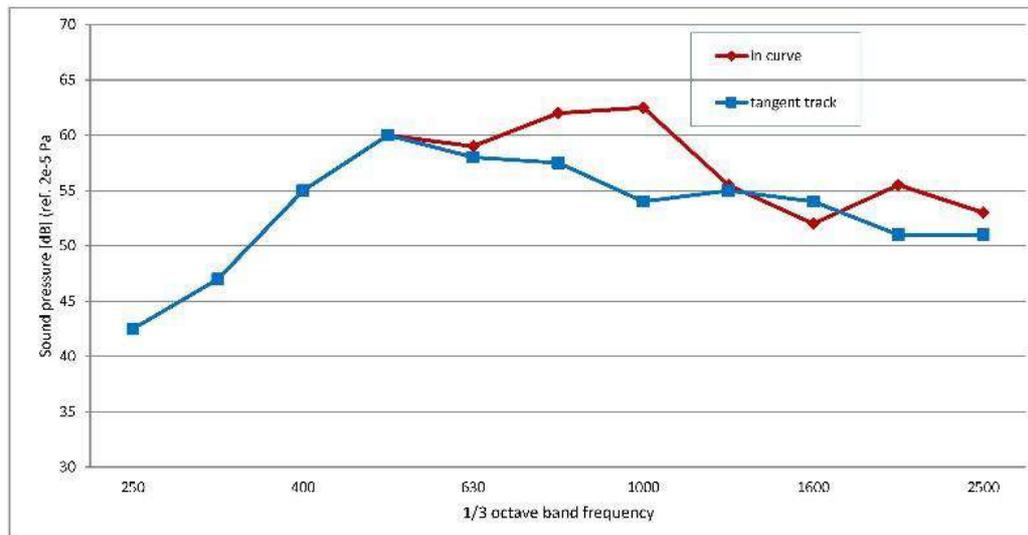


Figure 2: Rolling noise: comparison tangent track-curved track

3.1.2 Low frequency rolling noise emission model and software

A procedure for calculating the low frequency noise emission and propagation below 250 Hz is developed. In this methodology, the track and the wheel vibration level is computed using the Vehicle-Track Interaction (VTI) formulation as implemented in the WRNOISE software. Input parameters for the vibration level prediction are the track and the wheel admittance functions, TDR's, and the rail and the wheel roughness that are measured in the field.

Although numerical tools like WRNOISE exist for the prediction of rolling noise, they are limited to frequencies above approximately 250 Hz for several reasons:

- In prediction of the low frequency noise, the main challenge is in the computation of the radiation ratio. Although at high frequency, the radiation ratio tends to unity and has no significant effect on the noise level, at low frequency, it is frequency dependent and becomes more pronounced.
- In addition, at low frequencies, when the structure vibrates in bending modes with a wavelength shorter than the air wavelength, the acoustic short-circuiting effects may occur. In this case, only a near field radiation occurs and the sound radiation remains parallel to the surface of the structure.
- At high frequencies (higher than the cut-on frequency of the propagating waves in the track > 250 Hz), the track vibration is decayed along the track length because of the damping in the track (α) and the vibration level can be approximated by an exponential form of $v_0 e^{-\alpha x}$. The spatial averaging of the track vibration level in the WRNOISE is based on this approximation. At low frequencies where the track vibration consists only the near-field waves (a combination of the evanescent and propagative waves), the above approximation for computing the spatial average of the track vibration along its length is no longer valid.



- At frequencies higher than 250 Hz, the sound wave is coming directly from the structure (the track or the wheel) and the reflected sound off the ground acts as an incoherent source. However, the ground effect can be more important at low frequencies and depending on the type of the ground pavement, the sound pressure level can be increased by 6 dB.

A combined FE-BE methodology is proposed to overcome the above issues and to model the rolling noise emission at low frequencies (figure 3).

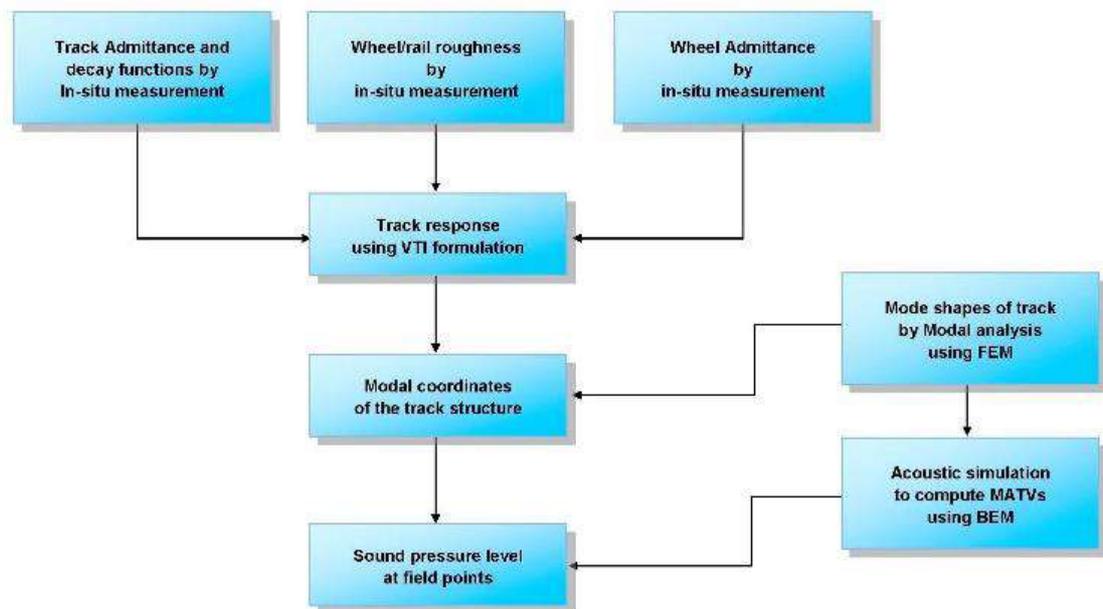


Figure 3: Combined FE-BE procedure for low frequency rolling noise

Main result

The proposed combined FE-BE procedure is integrated as a specific module within the WRNOISE software to predict the rolling noise emission at low frequencies (below 250 Hz).

In the acoustic simulation, the Modal Acoustic Transfer Vector (MATV) approach is used that results in an important reduction of the computation cost. In fact, the MATV approach enables to avoid the repetition of the acoustic simulation when the track structure remains unchanged but the vibration level on the track is changed due to different pass-by train speeds or due to different axle configurations.

The rolling noise levels at low frequency predicted with the proposed procedure shows a reasonable agreement with those measured in the field in Brussels (MIVB Tramway).

3.2 Rail surface monitoring by sound level – QT-system

The QT-system offers high quality monitoring of essential parameters related to noise generation from the main noise generating mechanism for railway vehicles at moderate speeds, the rail wheel interaction. By using simple sound pressure level measurements in in-service train variations in the essential parameters (combined wheel and rail roughness) can be determined on board of the train and submitted to land via the internet.

The measurement system consists of two bogie-mounted microphones, shielded by boxes. The boxes protect the microphones from the tough environment in the bogie and direct the microphones to the rail, which is to be observed. The system is complemented with another microphone pair to also monitor the track decay rate (TDR). The system also consists of an axle mounted high precision tachometer, a GPS-receiver, a front-end unit and a computer.

By using an in-service train, several passages of each track section will be measured each week. By using statistical analysis of all the measurement data high precision results for track roughness can be obtained on a weekly basis. Such data facilitate:

- Reduce noise and vibration generation by defining a maximum roughness level and thereby reduce the need for other noise mitigating measures e.g. noise barriers (especially in combination with efficient maintenance).
- Increase the accuracy in noise mapping (calculations) and measurements, as the roughness level is known at all times.
- Reduce the need for in-track inspections.
- Possibility to move towards status based track maintenance as the roughness growth process can be followed and maintenance activities can be planned well in advance.

Furthermore, the QT-system shows good possibility to detect severe wheel and rail wear in curves by using the same measurement data as above, but with another analysis process. By using trends and alarms from the system and increase lubrication in time, it is possible to increase rail and wheel lifetime (reduce costs) as well as reduce noise in curves.

The main advantages with the QT-system are:

- Possibility to use in-service vehicle:
 - No investment in measurement vehicle;
 - No need for time (in track);
 - A lot of measurement data facilitating high time resolution in the measurement series allowing for analysis of variations over time and for setting alarms.
- Low cost as the measurement system only use standard components.
- Possibility to transfer data via the internet as the data is processed on-board the train.

It has to be emphasized that this method allows to determine rail roughness value variations and TDR variations over time (relative values) and that the method is not suited for determining absolute precise values required as input values to the rolling noise models. The method is nevertheless a required complement to the rolling noise models since it gives insight in the variation of the input parameters (roughness, TDR) over time and it gives insight in the variation of these parameters over the length of the network. The prediction of track roughness shows a good agreement to absolute values for all wavelength bands related to the dominating noise at different speeds. Wheel roughness contributions are daily determined using order tracking to find out the roughness correlated to the wheel rotation. Wheel roughness can then be reduced from the combined roughness.

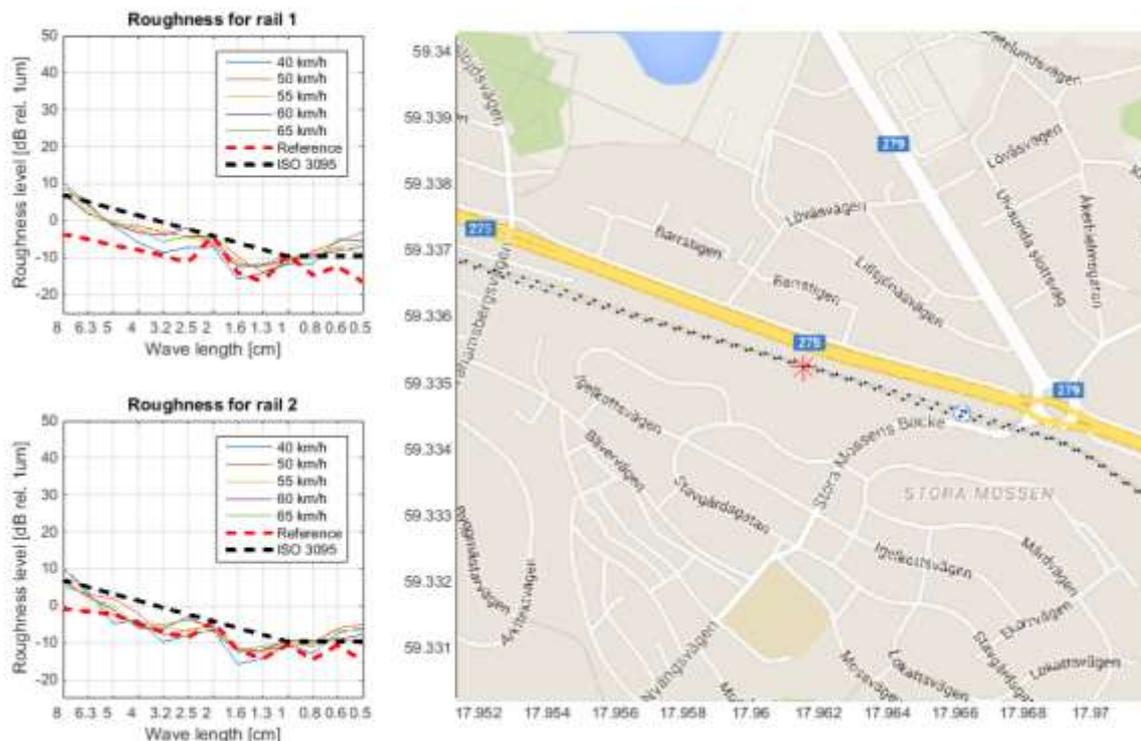


Figure 4: Example of result presentation, roughness level in one position along the track

The results from the monitoring system can also show how the sound pressure level increases in curves. In Figure 5 below, it is shown that the noise (close behind the wheels) is increased in the curves at 55 km/h and 65 km/h.

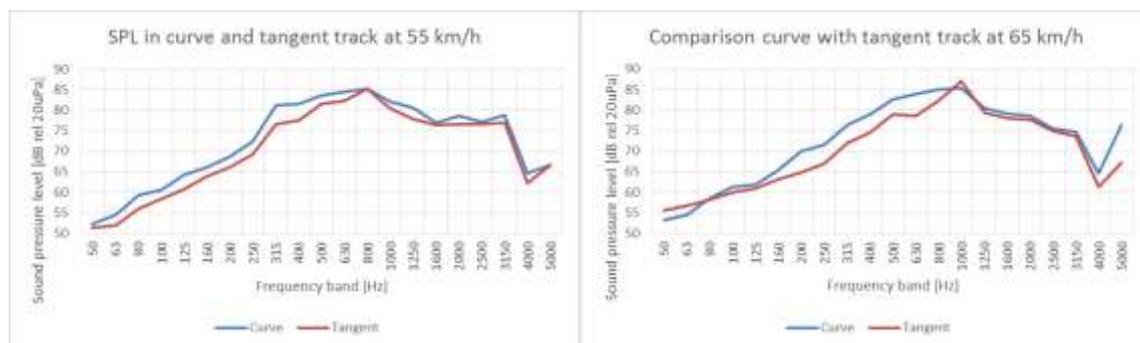


Figure 5: Sound pressure level in curve compared to tangent track in the Stockholm metro

In this case, the noise was increased by 2 dB(A) units in the curve.

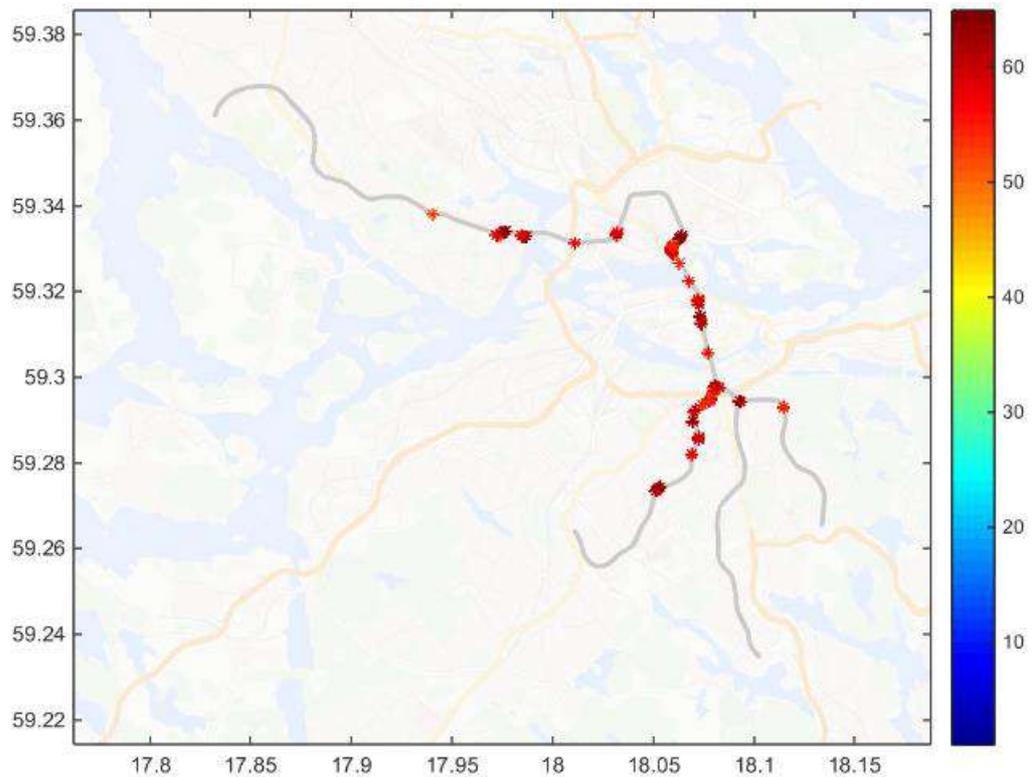


Figure 6: Example of result presentation, wear detection parameter above 40%, along track

All known locations with wear problems have been detected by the system.

During validation of TDR monitoring it has been found that the predicted indirect TDR agrees better with the direct TDR if the evaluation, of direct measurements, is modified so that only impact positions outside the reference near field are used and only positions between sleepers. The used positions also represent the same distance as between the on train mounted microphones.

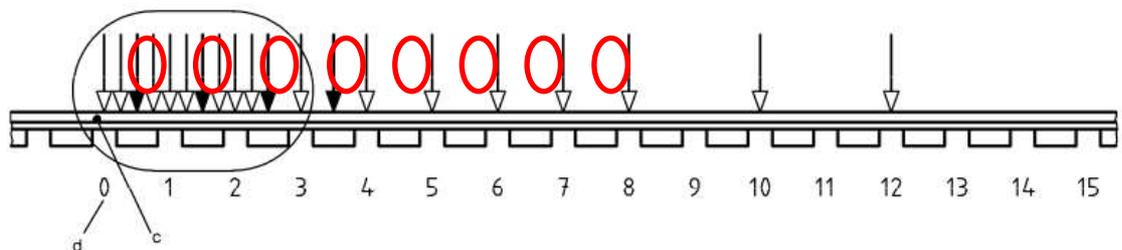


Figure 7: Excitation points on the rail when using the modified evaluation method of TDR
(d = inter-sleeper space; c = position of accelerometer)

The monitoring of track decay rate has shown how track decay rate varies with temperature. This has also been validated by use of direct measurements using an impact hammer and accelerometer. It can be noted that the track decay rate was changed by many dB/m for a change of only 15 C. It is therefore important to use a representative track decay rate in noise calculations. This further indicates the need of track decay rate monitoring as input for noise calculations.

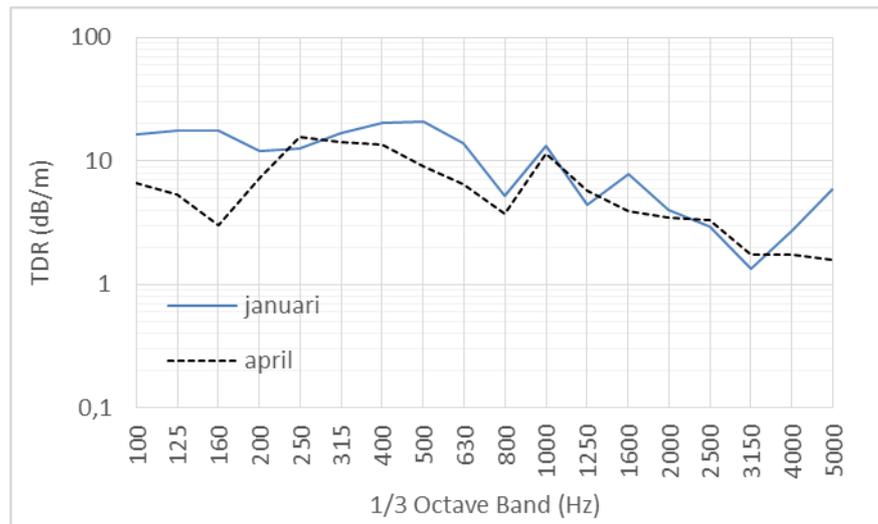


Figure 8: Direct measurement of vertical track decay rate performed in January (-10°C) and April (+5°C) at the exact same position. Measurements performed according to EN 15461

3.3 Input to rolling noise model

The rolling noise model requires a lot of input information. This input is described in the TSI Noise as well as the measurement or calculation methods to obtain that input. Following data are required: wheel and rail roughness data, track decay rate (TDR), wheel and rail impedances. Below alternative and new methods are developed in order to obtain the required information more accurately or more consistently over a larger area of the system.

3.3.1 Procedure for average wheel roughness determination

An inverse computation technique was developed to evaluate the wheel roughness using the measured sound pressure at receivers along an array of microphones beside the tracks. The track-vehicle interaction parameters such as the rail and the wheel receptances, the track decay rate (TDR), and the rail roughness are the other parameters needed for the inverse computation.

Since the irregularities at the wheel-rail contact are the excitation mechanism for the rolling noise, both the wheel and rail roughness are important input parameters for rolling noise calculation models.

Both rail and wheel roughness can be determined experimentally using dedicated measurement devices. Rail roughness can be easily measured at a specific location and there is a clear relation between the rail roughness and the measured noise level at a given distance from the track. The situation however is less obvious when it comes to wheel roughness. It is practically not feasible to measure the wheel roughness of all wheels of all passing vehicles.

Therefore, an inverse method is developed to determine the average wheel roughness of a given vehicle based on pass-by noise measurements of the same vehicle and parameters of the track at the measurement location.

Measurements have shown that wheel roughness is generally significantly lower than rail roughness, such that the rail roughness dominates the overall roughness in the wheel/rail contact. In those cases, the wheel roughness hardly influences the rolling noise and can therefore be neglected in simulations. Obviously, there is no need for the proposed method in those cases and the method becomes invalid, since it is



impossible to determine the wheel roughness based on pass-by noise measurements if the noise is not influenced by the wheel roughness.

Freight trains with cast-iron block brakes usually exhibit higher levels of wheel roughness. In that case, the proposed method is valid to determine the average wheel roughness of the vehicles.

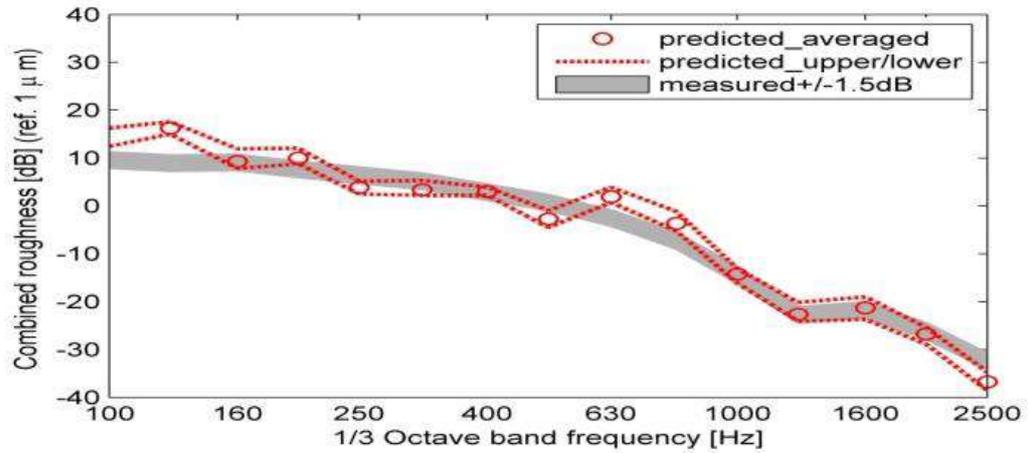


Figure 9: Calculated and predicted roughness (example)

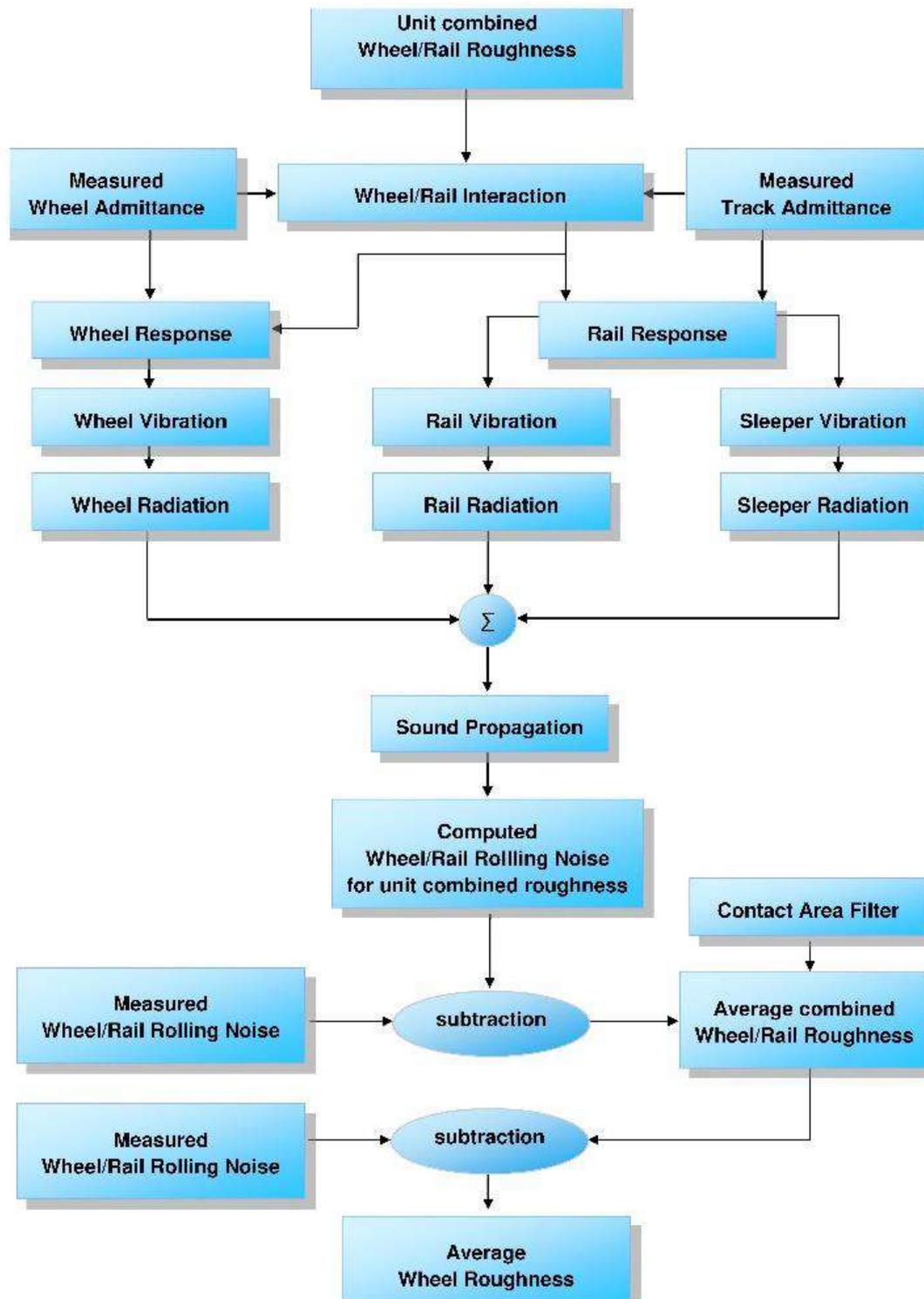


Figure 10: Inverse calculation scheme

3.3.2 Reducing the number of impact positions along track to determine the TDR values maintaining the stage of quality

Standard measurements for the determination of Track Decay Rates need a long time of staying in the danger zone of railway tracks. Hence, a technique would be preferable to reduce this duration significantly.



Due to some implications of carrying out these measurements, the most efficient way is a smart reduction of the recommended 29 impact positions by ISO 15461.

During the QUIET-TRACK project, some different methods of reducing the number of impact positions were investigated by ACCON.

First, a radical downsizing to a 2-position-measurement (this technique relates to the method invented during the STARDAMP project for the determination of Decay Rates under laboratory conditions at rails of finite length with mounted dampers) and a reduction of positions starting from the rear end of the measurement grid were investigated, but not worthwhile. A smart reduction of positions distributed along the grid led finally to a sufficient compromise between loss of accuracy and saving of time for TDR measurements. It could be shown, that a smart choice of positions down to remaining 11 impacts over a distance of 12 m are enough to determine TDR data with an aberration less than $0.15 \cdot \Delta \text{TDR}/\text{TDR}_{\text{orig}}$, e.g. at an original TDR value of 5 dB/m the resulting aberration would be in the range of $\pm 0,75$ dB/m.

These investigations were taken from 16 measurements at 6 different tracks without/with dampers at rail. The smart reduction of positions results in increasing deviation from the original data for lower frequency bands, which are of less interest for the determination of noise radiated by running trains. In the mid frequency range from 315 Hz up to 2 kHz the calculated deviation $\Delta \text{TDR}/\text{TDR}_{\text{orig}}$ is less than 0.1 dB/dB. The duration for carrying out the measurements in the danger zone of railway tracks is reduced from about 40-50 minutes down to 20 minutes.

3.4 Noise mitigation measures

3.4.1 Noise mitigation at the track using combination of existing mitigation solutions

The combined effect of different solutions has been simulated by using the enhanced Wheel/Rail Noise software, which incorporates wheel and rail roughness, wheel and track dynamic properties, track decay rate, vehicle parameters and vehicle speed. A specific section in the network of Attiko Metro line 1 (Athens, Greece) was selected with tangent concrete slab track emitting high rolling noise during vehicle passage at 40 mph. [4].

Three solutions were evaluated for noise reduction and their individual and combined effect was simulated. These solutions are: horizontal noise absorbing panels placed on the concrete slab, low height noise barriers close to the track and rail dampers. These solutions have also been installed consecutively and their effect on the emitted rolling noise has been measured at each installation phase. The global noise reduction performance is then compared with the simulations. The goals have been met.



Figure 11: Absorbing track panels



Figure 12: Rail dampers



Figure 13: Low noise barriers

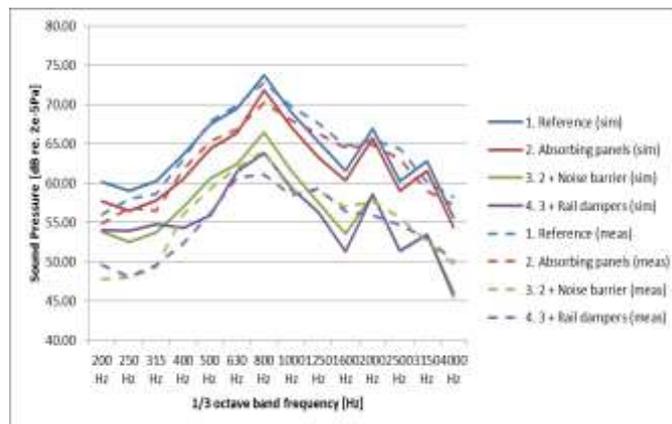


Figure 14: Measured and simulated noise spectra without and with the considered measures

3.4.2 Rail grinding as a noise mitigation measure

By development of the Track Maintenance Tool [5] continued by the Noise Management Tool [6], the importance of improved grinding strategies was pointed out. These grinding strategies will cause a noise reduction of up to 8 dB(A) if it is only applied to rails. An improved noise reduction of another 4 dB(A) by introducing a similar strategy for the roundness of wheel treads.

An additional win is achieved by this improved grinding strategy due to the increased life time of a rail under duty (figure 15).

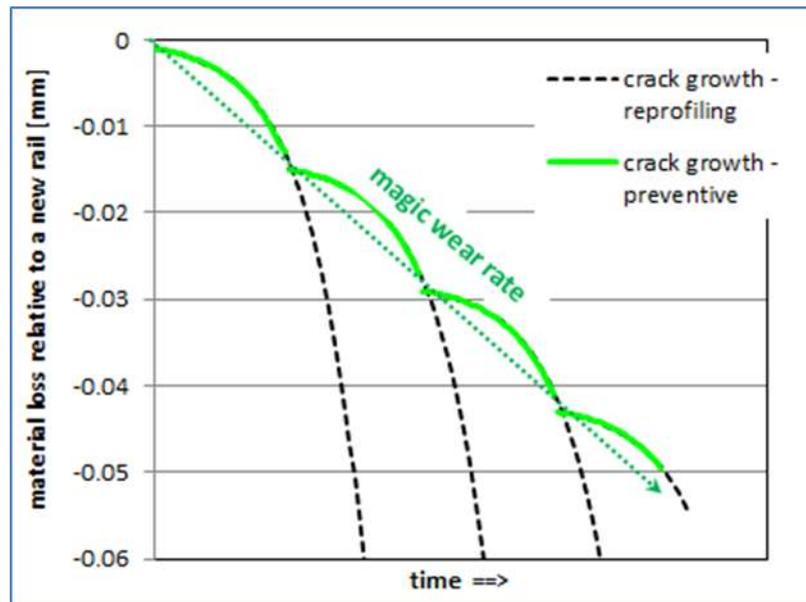


Figure 15: "Magic wear rate" as a result of preventive grinding

In TSI Noise, limit values for rail roughness on test track are introduced, overtaken in EN 15610 [7]. From the results in Quiet-Track, it is not recommended to take these limits as a stand-alone criterion for the classification of good or bad rail roughness conditions.

It is recommended to introduce in TSI Rail a qualification algorithm, which may be similar to the Noise Management Tool [6], to include environmental aspects in maintenance strategies, depending on affected habitants beside track. Due to the modern rolling stock based measurement systems for detecting rail roughness a wide

In addition to the conclusion mentioned above, it is recommended to introduce the single value indicator [8] as a descriptor of the rail roughness condition. In combination with other track parameters like Track Decay Rate (TDR) a comprehensive description of noise related track parameters are given.

3-4-3 Track solutions based upon reduced rail roughness growth

Track based noise mitigation solutions are developed based on the concept of reduced rail roughness growth rate. These solutions have a far better potential for noise control than the ones based upon increase of the track decay rate (TDR) since these last ones only reduce noise by 1-2 dB(A) on average. The potential of these track based solutions for rail roughness growth reduction is evaluated by the developed models and validated in the Infrabel network.

Three track based noise mitigation solutions based on the concept of reduced rail roughness growth rate are considered and installed in the network of Infrabel. The potential of each of these solutions has been evaluated based on the developed rail roughness growth model... Therefore, the track has been characterised dynamically; track decay rate measurements and track impedance measurements have been performed in all measurement sites before and after installation of the track based solutions.

The first considered solution is a highly elastic rail fixation system. The second considered solution consists of a standard M41 sleeper with a highly elastic wavy under sleeper pad. Finally, the third considered solution consists of a wide sleeper with a highly elastic wavy under sleeper pad.

Before and after installation of the track based solutions (including rail replacement), a long-term evaluation of rail roughness and rolling noise emission was performed; both the rail roughness and the rolling noise



were measured before rail replacement, after rail replacement and afterwards every 6 months and this over a period of 30 months.

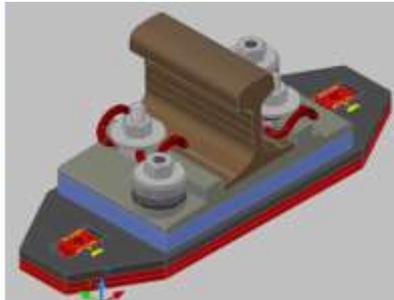
The long-term evaluation of the rail roughness and the rolling noise levels resulted in clear conclusions on the performance of the different track based solutions; in the section with a standard sleeper and wavy under sleeper pad, almost no rail roughness growth is observed after rail replacement. In the section with the highly elastic rail fixation, some rail roughness growth is observed, but the effect on the rolling noise is minimal due to the shift of the dominant rail roughness to a longer wavelength. Finally, in the section with the wide sleeper and wavy under sleeper pad, a more rapid rail roughness growth was observed, with a visible corrugation pattern. Overall, the rail roughness remains well below the levels that were observed before rail replacement and the overall noise level remains well below the level before rail replacement.

A clear relation was established between the measured rail roughness and the rolling noise spectra (figure 16).

Track based solutions are now available which do not inhibit rail corrugation initiation or growth. This is a major and unique result in the rail infra area.

Considered solutions

- S1 – Elastiplus direct fixation on concrete sleeper



- S2 – M42 sleeper with wavy under sleeper pad



- S3 – HDS wide sleeper with wavy under sleeper pad



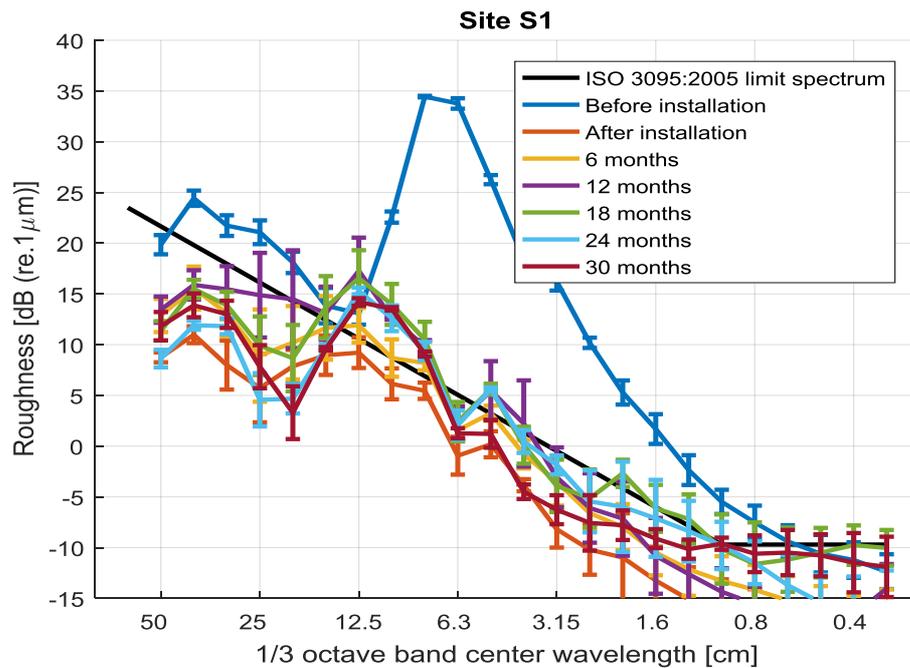


Figure 16: Evolution of rail roughness (corrugation) in function of time for elastiplus solution

3.4.4 Acoustical embedded rail

Experiments carried out in the tram network of The Hague (The Netherlands) show that a rail which is completely embedded within a sand bed yields noise reductions of up to 10dB(A). Elastically embedded rails are already in use for vibration reduction. This track type is optimised for its noise mitigation performance whereby all noise sensitive parameters are considered and linked to track design parameters such as stiffness and damping of embedment material, use and characteristics of the continuous rail pad. This optimisation process is validated in the network of De Lijn.

Rolling noise simulations have been performed to optimise the characteristics of standard embedded track types in use by De Lijn. This has resulted in the selection of two acoustically optimal track systems, which are also very good in terms of stability and low maintenance. One system is for direct fixation on concrete, the other system uses concrete sleepers inserted in the concrete track slab. Both of these track types have been installed: one in Ghent (Papegaaistraat) (see fig.17) and one in Antwerp (Bredabaan) (see fig.18). Full experimental characterisations of both tracks and acoustic validation measurements have been performed. The validation shows an excellent agreement of the simulated results with the measured results and shows good acoustical performance.

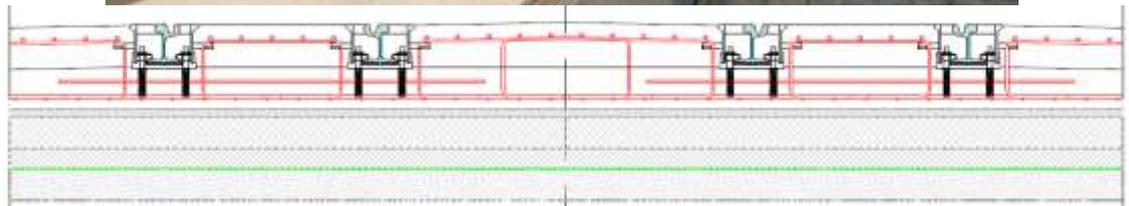


Figure 17: Developed low noise embedded track system in Ghent (Papegaaistraat)



Figure 18: Developed low noise embedded track system in Antwerp (Bredabaan)



3.4-5 Rail type and hardness selection for optimal acoustic performance and wear

Rails are subject to wear and this wear growth is strongly influenced by the selection of the rail type (and hardness) in function of the type of rolling stock. The goal of this task was to develop a procedure to select the optimal rail type in terms of minimal rolling noise emission combined with optimal wear characteristics taking into account tangent track and curved track.

An extensive measurement campaign has been performed in the network of De Lijn in order to assess rail wear growth over a 3 year period under different circumstances; the influence of the curve radius, rail type and hardness, vehicle type and presence of a station (in order to assess the effect of acceleration and deceleration) has been investigated. These measurements have been statistically processed taking into account the annual axle load in each of the measurement locations.

Although such measurements clearly show the absolute rail wear in the different locations under different circumstances, it is difficult to assess the influence of the different parameters on the rail wear independently and to draw conclusions from these measurements alone. Therefore, a multibody simulation model is used to perform the required sensitivity analysis. The multibody simulation model consists of a vehicle model and a track model. The vehicle is an exact representation of the "Hermelijn" vehicle used by De Lijn. The car bodies and bogies are represented as accurately as possible; the mass distribution, position of the center of gravity, moments of inertia and the characteristics of springs and dampers has been determined accurately. The track model is a typical trajectory with a tight curve. It includes the exact representation of the rail profile and takes into account the rail hardness.

Based on the in-situ measurements, the multibody wear simulation model has been validated. After the validation, a sensitivity analysis is performed to investigate the influence of the different track (and vehicle) parameters (figure 19)

The wear model is to be used in conjunction with the wheel-rail rolling noise model extended for multiple contact points to predict noise emission from worn rails.

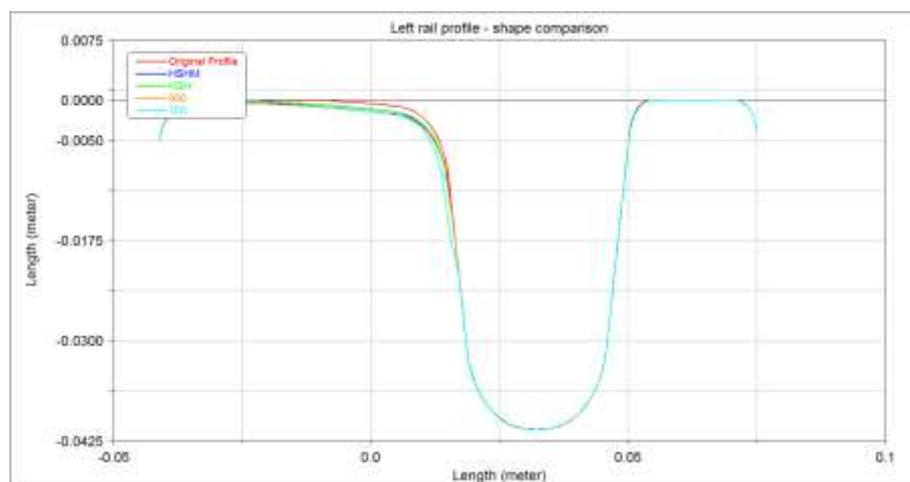


Figure 19: Rail wear simulation for different rail hardness (example)

3.5 Noise related track maintenance tool (NMT)

The primary goal of the NMT is establishing cost-optimized noise reduction within urban railway networks. In a database with easily customizable interfaces (see figure 20), it collects data representing the state of the network and fleet, such as:

- monitored rail and wheel roughness,
- noise-related rail wear,
- maintenance cost for acoustic grinding and wear removal,
- the life cycle costs of the network.

An interface to noise-mapping software allows the track-segment specific analysis of the noise distribution and the determination of the resulting annoyance, based on geo-referenced inhabitant data. This facilitates the determination of noise damage costs based on approved cost factors.

The NMT gives responsible infrastructure managers (authorities) the ability to oversee rail roughness and its development over time, for every single network segment. It is able to predict the performance of noise mitigating measures, and to select optimally the type of track mitigation measure. This is important for example in action plans as requested by the Environmental Noise Directive within cities, where non-track-based measures are often not feasible. The NMT also allows determining the maximum achievable noise reduction for the available maintenance budget and within the applicable maintenance-operation time-frame.

Furthermore, detection and analysis of reasons of abnormal roughness growth are possible. Thereby the noise situation along the track network can be investigated and contrasted with the monetary benefit from noise reduction along the network. Eventually, the noise management tool allows quantifying the performance of noise mitigating measures with emphasis on optimized grinding.

With easily customizable interfaces, the NMT can be integrated in a specific network's existing infrastructure without adapting or modifying the established system structure or its components.

Main advantages

- The NMT facilitates monitoring and management of:
 - track & fleet status (incl. maintenance, e.g. grinding);
 - noise emissions, immission, & reduction measures.
- Development of cost-optimized maintenance strategies.
- Simple integration in the existing infrastructure.

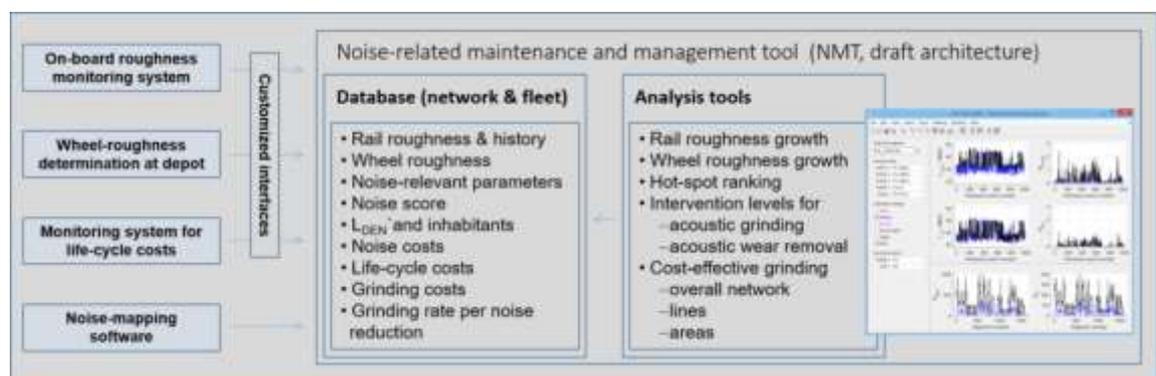


Figure 20: Noise-related track maintenance and management tool: system architecture, interfaces, and analysis tools

References

- [1] EU Directive 2011/275/EU Technical Specification for Interoperability relating to the 'infrastructure' subsystem of the trans-European conventional rail system notified under document C(2011) 2741



- [2] EU Directive 2011/275/EU Technical Specification for Interoperability relating to the 'infrastructure' subsystem of the trans-European conventional rail system notified under document C(2011) 2741; ANNEX F LIST OF OPEN POINTS Noise and vibration limits and mitigation measures (4.2.11.2)
- [3] EU Directive 2011/291/EU Technical Specification for Interoperability relating to the rolling stock subsystem — 'Locomotives and passenger rolling stock' of the trans-European conventional rail system (notified under document C(2011) 2737)
- [4] Quiet Track Deliverable 4.2; Validation section in network of Attiko Metro with optimal combination of existing solutions; TTE
- [5] Quiet Track Deliverable 3.3; Noise related Track Maintenance Tool; ACCON
- [6] Quiet Track Deliverable 5.3; Noise Management Tool for introduction of track based noise mitigation solutions: Noise Management Tool for introduction of track based noise mitigation solutions; ACCON
- [7] DIN EN 15610 Railway applications - Noise emission - Rail roughness measurement related to rolling noise generation; German version EN 15610:2009
- [8] HARMONOISE ; DEFINITION OF TRACK INFLUENCE: ROUGHNESS IN ROLLING NOISE; Appendix 7 Single value indicator for roughness L_{rCA} ; Project funded by the EC under the Information Society and Technology (IST) Programme; 2003