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# A REVIEW OF RAILWAY NOISE RESEARCH AND RESULTS SINCE THE 5th IWRN IN VOSS (NORWAY)

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Since the 1995 International Workshop on Railway Noise in Voss, two major elements may be considered as influential to railway noise research:

— there is a clear and strong demand, at the European level as well as nationally for reducing railway noise in terms of operational solutions, especially for freight traffic,
— theoretical developments for modelling rolling noise (which is the major source of noise for conventional speed) reached a point where operational developments of low noise solutions could be successfully carried out with the Twins model.

Accordingly, research focused on developing such low noise solutions for rolling noise, investigating subsidiary and still unanswered questions, and addressing outstanding problems related to aerodynamic noise. In parallel to these propagation and annoyance studies were the subject of continuing interests, either with practical results or detailed on-going studies. Finally, modelling interior noise either with modal approaches for lower frequencies, or with SEA for higher frequencies, have proved successful in the case of high speed. Emerging subjects involve a revival of groundborne vibration modelling, roughness generation studies and decision management systems to get the greatest benefit from various potential solutions.

## 1. INTRODUCTION

Since the last International Workshop on Railway Noise held in Voss in 1995, legal, environmental and research needs have been identified and addressed.

When considering the legal requirements, as national systems continued to be built, in, for example, Italy and France, a major development was the initiative taken by the European Commission following the Green Paper on Noise to establish a European policy on noise, which will of course include railways.

Despite the fact that railways had not waited for legal pressure to lower the noise emitted by trains (the 10 dB(A) reduction already achieved by high-speed trains can be compared with the 5–8 dB(A) reduction in the period 1982–1996 legally imposed on the road sector), acknowledgment of the role played by the railways was not clear until very recently, when joint initiatives from European railways were officially reported to the European Commission. However, there remained a clear need for estimating the noise reduction potential at source for the railways, as well

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as a demand for concrete reduction measures. This in turn influenced research practices towards shorter-term developments of low noise solutions for two reasons. First, there was pressure from both national and European authorities for the development of operational low noise concepts; and second, basic mechanisms for rolling noise (which is the major source for railway noise at conventional speeds) are now understood. This made the developments of reduced noise solutions possible.

The evolution of research on rolling noise, including the development of low noise solutions, will be considered first. Later research on aerodynamic noise, will then be considered in terms of technological outputs. Solution in the field of barriers, propagation and annoyance will then be given. Finally, emerging or revisited fields of research will be considered.

## 2. ROLLING NOISE RESEARCH

### 2.1. BASIC RESEARCH

In previous work, the basic generation mechanisms of rolling noise had been defined, through the TWINS (Track–Wheel Interaction Noise Software) building and validation [1, 2]. The TWINS model had been validated against several configurations of rolling stock (passenger, freight and TGV [3]) and tracks in Europe with a discrepancy between prediction and tests not exceeding 3 dB(A) in the worst cases.

The validation tests for TWINS had revealed a need for further modelling of the track vibration. Indeed the vibration models available in TWINS at that time incorporated either discrete support modelling, which enabled the “pin–pin frequency” to be represented, where a flexural mode occurs between two sleepers considered as a rigid support, or cross-sectional deformation of track on continuous supports.

A refined model of track, resting on discrete supports, but allowing rail cross-sectional deformation, was then developed [4, 5]. Rail accelerances could then be predicted more accurately within the 1000 to 5000 Hz range.

This model, called VIBRAIL is being incorporated into TWINS in order to improve its accuracy in terms of rail vibration prediction.

An example of calculation of vertical accelerance calculated by VIBRAIL, compared with previous calculations is given in Figure 1.

The full potential of VIBRAIL will in fact be obtained when refined acoustic modelling of the track has been developed. This work is presently under way inside the EU project SILENT TRACK.

### 2.2. ALTERNATIVE PHENOMENA

One potential mechanism for rolling noise generation, which has been shown to be at least second order with respect to the influence of wheel and track roughness, is stick-slip in the wheel-rail contact patch.

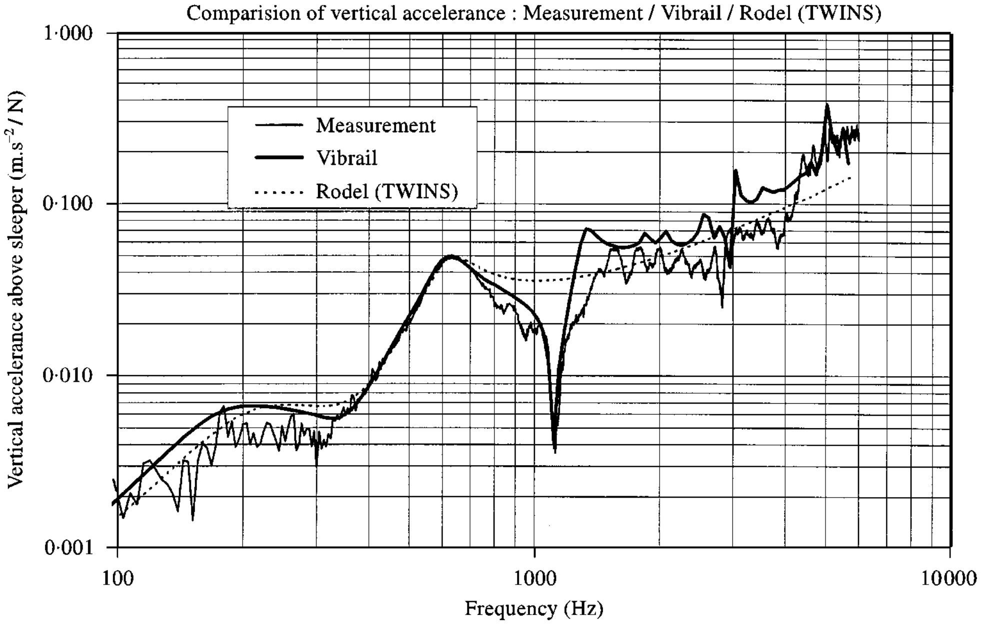

Figure 1. Comparison measurement/Vibrail/Rodel (TWINS). ———, measurement; ——, Vibrail; - - - -, Rodel (TWINS).

In order to be able to quantify better the potential influence of this phenomenon, tests were carried out within the DEUFRAKO (Deutsche-Fransözische coooperation) both on TGV and ICE trains.

In situations where "stick-slip" is likely to occur, no evidence yet appears to have demonstrated stick-slip-induced noise.

Another phenomena studied using an alternate model developed at KTH (Sweden) and further improved at TUB [6] is the influence of the pad characteristics in terms of stiffness, damping and spacing [7]. It appeared during DEUFRAKO studies that single-frequency rays characteristic of periodic systems are transformed into wider band peaks and accompanied by a rise in the background level when random variations are added to these parameters. This phenomenon could be of interest not only for low-frequency noise but also for passenger comfort.

## 2.3. OPTIMISED SYSTEM DEVELOPMENT: FREIGHT TRAFFIC

As the basic mechanisms of rolling noise generation are now understood, through the TWINS (Track Wheel interaction Noise Software) model building and validation [1, 3], and as the principles for wheel [8] and track [9] optimization have been settled, there was then a need for the practical implementation of these concepts. This work was carried out at European Rail Research Institute (ERRI), through the Optimized Freight Wheel and Track (OFWHAT) project, dedicated to reduction of freight traffic noise. Within this project, several types of tracks were specified, either by tuning the stiffness of the pads, or by designing rail vibration

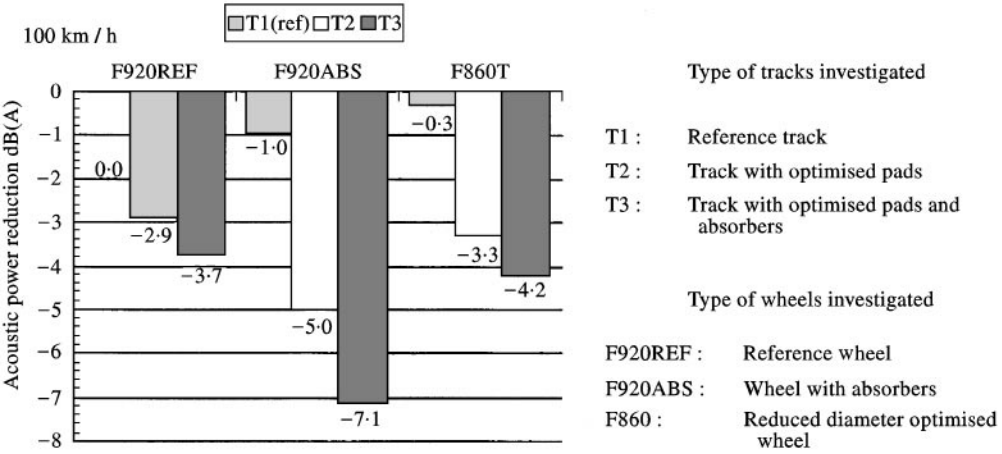

Figure 2. Noise reduction obtained with the OFWHAT project of freight vehicles different racks (100 km/h).

dampers. In parallel, vibration dampers were designed for conventional 920 mm diameter freight wheels, and the shape of a reduced diameter (∅ 860 mm) wheel was optimized with respect to vibration and noise emission. The experimental results [10]) confirmed the calculations carried out with TWINS, in that noise reductions ranging from 3 to 7 dB(A), depending on the configuration (Fig. 2).

These results in turn were the starting point for gathering two consortia involving industrial manufacturers to launch the Brite-Euram projects SILENT FREIGHT and SILENT TRACK, in which a thorough investigation of potential designs for both low noise vehicles and low-noise tracks is being carried out.

In the SILENT FREIGHT project, two concepts of optimized wheels are being assessed: one in which short-term development could be carried out and another in which more drastic changes in concepts of wheel designs are investigated using TWINS. Industrial prototypes will then be developed and tested in 1999.

In parallel, the influence of superstructure noise has been investigated and the effects of changes in the design of the superstructure has been assessed using SEA modelling.

In the SILENT TRACK project, extensive investigations of potentially quieter track has been conducted. In this respect, as well as investigations of changes in pad stiffness, vibration absorbers will be designed, and new rail shapes and a new type of rail fastener are being developed. A parallel modelling of roughness generation and growth will ensure that the technical option chosen for prototyping will not result in faster roughness generation or corrugation effects.

## 2.4. OPTIMIZED SYSTEM DEVELOPMENT: HIGH SPEED

In a parallel way as developments carried out at ERRI, optimized wheel–rail configurations were studied for high-speed trains [11]. Optimized shaped wheels, equipped with absorbers of different kinds, were developed, and rail pads and track absorbers adapted to TGV track were prototyped.

The experimental results confirmed the order of magnitude of the achieveable reduction by a combination of wheel and rail response and radiation control devices. A significant reduction could only be obtained by combining measures on the wheel and on the track. Moreover, overall reductions of 1–2 dB(A) obtained with the noise-optimized wheel, on reference track, ranged up to 6 dB(A) when the pads were stiffened, and 8 dB(A) on the track equipped with absorbers.

### 2.5. OPERATIONAL IMPLEMENTATION OF SOLUTIONS

Until now, operational strategies to reduce rolling noise were mainly devoted to reducing wheel roughness. New generation of passenger rolling stock for intercity trains were designed with disc brakes. The removal of cast-iron shoe brakes, which reduces wheel roughness, gave a reduction of rolling noise that was estimated to range up to 10 dB(A).

For high-speed trains, a similar approach was undertaken with the generation of TGV-Atlantique and later series. By removing the shoe brakes on the trailer cars, the $L_{Aeq},_{tp}$ (equivalent level over the pass-by time) noise level at 25 m decreased from 99.5 dB(A) at 270 kph for *TGV-South-East* to 94.5 dB(A) at 300 kph for *TGV Atlantique*, *Reseau* and later series. The introduction of composite brake blocks on the motor cars, is expected to provide a further overall reduction of 1.5 dB(A). With the levels of roughness obtained of the wheels, the rolling noise level is becoming increasingly dependent on the track roughness levels, making it necessary to develop roughness monitoring devices, as well as a roughness-oriented track maintenance policy. As a radical solution, the shoe brakes have been totally removed on *TGV-Duplex* series. This, in combination with adequate designs towards aerodynamic noise, would entail nearly 10 dB(A) reduction for *TGV-Duplex* noise with respect to *TGV-Sud-Est* earlier series.

As far as suburban or regional trains are concerned, the trends are that, as soon as braking specifications are met and thermally induced stresses on wheels are acceptable, cast iron or even sintered brake blocks will be replaced by composite ones [12]. Lower lifecycle costs through a longer life of composite brake blocks have been achieved.

The problem is much more difficult with freight wagons. It was shown that even if individual railways replaced cast-iron brake blocks by composite ones [13], an overall acoustic effect as well as the absence of other non-acoustic effects in trains (different rates of braking leading to excessive longitudinal loads), could only be reached by an international joint initiative. This is in turn under consideration; an international homologation procedure for composite brake shoes selection is being developed, and a joint initiative for common implementation, when technical safety problems have been solved, is being proposed by UIC (International Union of Railways) [13].

## 3. AERODYNAMIC NOISE

### 3.1. IDENTIFICATION AND INVESTIGATION OF AERODYNAMIC SOURCES

For the three European high-speed systems (ICE, TR07 and TGV) the noise sources including aerodynamic ones has been identified [14] in the German French program DEUFRAKO. A detailed investigation of these individual aerodynamic noise sources has been undertaken [15], combining wind tunnel and line tests, together with the development of specific measurement methods. The detailed frequency content and an estimate of the acoustic power of each source identified is now available. This information will be gathered in a new general model for train noise, giving the potential of overall reduction in function of the reduction obtained on each individual source.

For the Japanese high-speed trains, which run most of the time behind noise barriers, aerodynamic noise comes mostly from the upper parts of the train. Special analysis methods have been developed [16], and an anechoic high-performance wind tunnel was recently put into service in MAEBARA (Japan).

### 3.2. BASIC RESEARCH AND MODELS FOR AERODYNAMIC NOISE

Existing models for aerodynamic noise applied to railway configurations have come essentially from the works on TBL or pantograph [17]. As work in the aeronautical sector was mostly devoted to jet noise, the theoretical development of basic models of an impinging wall, backward and upward facing step noise was undertaken [18]. The combination of these models will in turn enable the building of models for such practical configurations as the pantograph recess.

These models were built, with acoustic simplifications, from a Reynolds averaged Navier–Stokes (RANS) calculation approach of the flow. Recently, opportunities to use operational simulations including refined knowledge on turbulence have come about with the development of large eddy simulation (LES) which gives a better insight into non-stationary turbulence phenomena, without the complexity of solving the full Navier–Stokes equations. Implementing such approaches for aeroacoustic simulation seems promising in a middle-term future.

### 3.3. TECHNOLOGICAL DEVELOPMENTS AND IMPLEMENTATION

A technological programme aiming to assess the potential of solutions such as shielding, masking the shape of the inter-car gap, etc, was carried out, essentially using wind tunnel testing combined with RANS computation [19] of turbulence creation by train shape discontinuities.

Implementation of solutions to reduce the noise of the pantograph were carried out within the German–French programme DEUFRAKO, which lead to an overall 2–3 dB(A) noise reduction measured in the pantograph region, though 5 dB(A) reduction was obtained on the pantograph alone.

## 4. NOISE BARRIERS

### 4.1. MODELS AND CALCULATION METHODS FOR BARRIERS EFFICIENCY

Several theories are currently being used to assess barrier efficiency. Apart from the well-known MAEKAWA theory, which is still efficient for operational dimensioning, several approaches were attempted, using either geometrical theory for diffraction or other more refined tools, but based on ray-tracing methods. These methods are well suited to operational calculation of barrier efficiency, as they allow 3-D calculations.

Among them, TOMAS (TNO-NL) [20] or MITHRA (CSTB-F) [21] have both been assessed against experimental data, the first one within the Brite-Euram EUROECRAN project [20]. Alternatively, some development of the 2-D boundary-element method was carried out within the Euroecran project [20], and an extension of this approach to 3-D calculations was shown to be possible [22]. The boundary-element method appears more suited to the calculation of complicated shapes of barriers in terms of defining characteristics of the shape of the barrier, but it can also be used to assess the efficiency of systems placed on the top of the barrier, which are claimed to enhance the efficiency of the barrier [20].

In all cases, the key element to success for railway applications is to take into account the possible interaction between the barrier and the carbody, a situation which very scarcely occurs in non-railway (road traffic) applications. This interaction was shown to be crucial both in the calculation and reduced size or full-size modelling of train barrier.

Moreover, in the frame of the EUROECRAN project, reduced size as well as full size but reduced length methods of testing barriers were developed and compared. A methodology to assess barrier insertion loss from real trains pass-by was also developed [20].

### 4.2. IMPROVED EFFICIENCY AND REDUCED COST BARRIERS

In the EUROECRAN project, more than one hundred possible candidates for barriers of improved efficiency were considered. Twenty of them were initially selected through calculation of their compared efficiency, and 12 were tested either in reduced size or reduced length. Finally, three types of barriers were tested on real sites.

An increase of efficiency of 2–3 dB(A) in term of insertion loss, along with a potential of 20–30% cost reduction was obtained.

In a study sponsored by UIC/ERRI (European Rail Research Institute) [23], devices on the top of barriers as well as low, close barriers were assessed by calculation. It appeared that in order to be effective, two parallel low barriers had to be designed, or low barriers had to be combined with classical ones. An implementation of the latter concept was recently implemented in the centre of Oslo.

## 5. PROPAGATION

Work on propagation, taking into account meteorological conditions (wind and temperature gradients) though not specific of railways applications, was undertaken. As meteorological influence is conventionally taken into account in the regulations of several countries, a method of calculating propagation accurately in the presence of wind and temperature gradients was developed [24]. In the meantime, the NMPB (Nouvelle méthode de Prévision du Bruit) [25] was developed for road traffic in France and is being currently adapted to railway noise.

In the latter method, according to the "local" meteorological conditions (dominating winds), the long-term value of the $L_{Aeq}$ is calculated for both favourable to propagation conditions and "homogenous" (no wind or temperature gradients) situation. Other studies including the influence of meteorological effects were also carried out [26]. During the recent EU conference on noise policy (Copenhagen, Sept 7/8, 1998) construction of a common EU prediction method incorporating the most advanced elements from the various developments in Europe was suggested and discussed.

## 6. ANNOYANCE

Several studies related to annoyance were also started and initial results were presented in the conference. The subjects covered included annoyance in multi-exposure (road/rail) situations, perception of barriers efficiency or sleep disturbance by noise. It seems also clear from the Copenhagen conference that $L_{Aeq}$ may be adopted as the agreed basic operational indicator for annoyance, even if in particular situation complementary annoyance descriptors still to be validated, might also be used.

## 7. EMERGING IDEAS

### 7.1. ACTIVE NOISE CONTROL

Active noise control has received considerable attention for the past few years, mainly for interior low frequency and narrow band noise applications. An investigation of the potential of ANC for exterior noise was undertaken by ERRI. The applications found to be the most promising for exterior noise could be ANC in addition to barriers in the vicinity of stations [27], or on platforms to try to cancel locomotive fan noise.

However, the control system performance, as well as the actuator technology does not seem to provide practical applications in the near future.

For interior applications, ANC could have potential for reducing the noise in the driver's cab of older series of engines, as a retrofit application. Practical feasibility and cost still have to be assessed.

### 7.2. ROUGHNESS GENERATION AND CONTROL ON WHEELS AND RAILS

Wheel and rail roughness are now well known to be key elements in rolling noise generation. In severe cases, i.e., rail corrugation, experimental as well as modelling work [7] [28] [29] emphasized the role played by track stiffness in rail roughness generation. This in turn suggests that an acoustical optimization of track stiffness parameters should be approached systemically, taking into account as far as possible, the roughness generation aspects.

On the other hand, an investigation of the specification requirements of coatings which could be efficient in reducing roughness generation on rails was undertaken by ERRI. The difficulty of such a study is primarily the potentially conflicting requirements of meeting the classical railway operational constraint for traction and breaking and preventing roughness generation.

Roughness generation on wheels received much more attention in the EU sponsored EUROSABOT project [30]. The mechanics of a wheel during braking was studied carefully and a better basic knowledge of roughness generation on wheel could come from developing the ideas investigated in this project.

### 7.3. NOISE FROM BRIDGES

This subject was the subject of modelling with SEA [31] and quiet bridges prototypes were developed [32].

## 8. INTERIOR NOISE AND PASSENGER COMFORT

The last three years also saw the development of refined modelling for interior noise and passenger comfort. While previous designs in terms of interior noise relied mainly on classical mass laws, successful application of statistical energy analysis (SEA) was carried out for interior noise of high-speed trains due to aerodynamic sources. The applicability of SEA in terms of frequency range proved efficient for frequencies ranging down to 250–300 Hz, a domain which was previously thought to be relevant to a "medium-frequency" approach rather than SEA. On the other hand, an approach based on modal decomposition, where a special treatment was applied to calculate the modes of the coach side walls in order to take into account the windows, was successfully applied for frequencies ranging up to 50–250 Hz [33]. An example of such a calculation, as compared with test, is given in Fig. 3.

Whatever the approach, since the "medium-frequency" range might not need, in such cases, a separate treatment, a major issue would then be a comprehensive and efficient method to assess solid or in air transmission of "low frequency" (50–300 Hz) noise, as well as an identification of the real causes of such low-frequency noise (track defects, parametric excitation as harmonics of sleeper passing frequencies, or wheel defects).

Answering such questions may again involve combined wheel–rail interaction analysis.

## 9. GROUNDBORNE VIBRATION

Groundborne vibration is not a new problem as it is recognized as a companion problem to noise. Nevertheless, noise propagation, being easier in most cases than vibration propagation, noise questions seemed to have attracted at least more co-ordinated research effort.

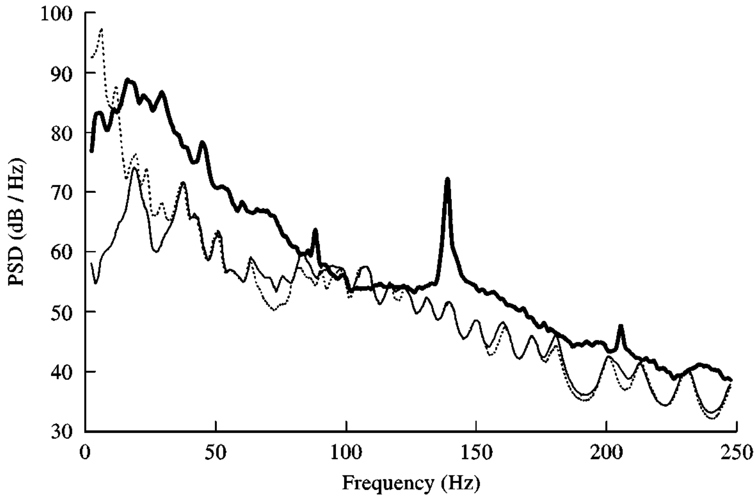

Figure 3. Acoustic pressure inside TGV coach using CAPHCA code in low frequency domain. ......., Model 1; ——, Model 2; ——, Measurement.

Groundborne vibration problems, already investigated in several papers in Voss, has already received attention in Great Britain, Norway, Germany and Switzerland, by modelling or as tentative candidates for mitigation measures. A number of empirical approaches or models, have also been developed.

An initiative recently taken by ERRI through the RENVIB project, was first to review most of the research effort carried out in the past few years which applied to railways. In a second stage of the project pragmatic assistance will be provided to ongoing mitigation projects, whilst a third stage of the project will build from these experiences to develop a general model for vibration generation for a railway track. This model should enable the systematic development of national mitigation measures to reduce groundborne vibration in a very similar approach to the one carried out with the TWINS model for rolling noise.

## 10. COST–BENEFIT ANALYSIS AND DECISION MANAGEMENT SYSTEMS

As noise reduction involves combined measures at source or by means of the so-called "passive" methods such as barriers, a natural question is how to combine the application of several techniques for a given situation in the most cost-effective sense.

This approach was considered in Switzerland where, through a detailed mapping of 1000 km of the Swiss network, it was shown that 70% of the problem was solved by 20% of the cost of solving noise problem extensively [34]. This study implied the development of a detailed monitoring and decision helping tool [35].

A similar approach was undertaken in the Netherlands through the GERANO system development [36]. These initiatives are now being used in a UIC project where the basis for a European system assisting the decision process would be set along with demonstration cases on freight corridors.

Considering the future development of various potential solutions on rolling stock, tracks, and optimized noise barriers, such tools might in the future be a prerequisite for investment decisions at national or even international levels.

## 11. CONCLUSION

Railway noise research developed during the past three years following two major trends:

— the need for operational solutions to reduce noise problems by national or European institutions and,

— the availability of a model for rolling noise and concepts for developing low-noise railway systems, enabling the development of low-noise prototypes.

Results concerning rolling-noise involved prototype demonstrations for both freight and high-speed trains showing a noise reduction of 3–7 dB(A). Aerodynamic noise and roughness generation are still being investigated. Developments in prediction of noise propagation showed an improvement in barrier efficiency and the means of accounting for meteorological conditions. Finally, increasing interest in re-visiting groundborne vibration, the development of models for interior noise prediction and decision support systems could be the key issues for future directions in railway noise research.

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