The real cost of railway noise mitigation

A risk assessment

Union Internationale des Chemins de Fer

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EXECUTIVE SUMMARY

National noise legislation requires rail infrastructure managers throughout Europe to take noise mitigation measures. Practically, the choice is between vehicles related measures (for example brake shoe retrofitting), track related measures (for example rail dampers), measures in the propagation path (for example noise barriers) and measures at the receiver (for example double glazing). The costs of the different measures are a crucial parameter when making this choice.

The common rail position is that rail freight retrofitting is the most cost efficient measure. This position was underlined in the UIC Noise Action Plan, adopted in 1998. This notion was based on the results obtained in the research project STAIRRS, where the costs of different mitigation options were compared. The results of STAIRRS have been quoted many times since they were first published. Almost 15 years have passed since. Therefore, the current study was launched with the objective to review and update the information on which the STAIRRS results were based. Particularly the current study addresses the fact that cost data should be based on life cycle cost assessment rather than merely investment costs in order to have a fair comparison between options.

In the frame of the current study, an attempt was made to collect practical data on cost elements such as maintenance costs and life span of certain measures. For rail freight retrofitting, such an assessment has been made in full detail, and the intention was to compare this data with similar data for the other options. In addition, information was collected on the amount of noise migration required in the different member states, based on current legislation. It was found, that very little detailed information is available from the infrastructure managers. Usually, once the noise mitigation measure has been installed, the costs for its maintenance are hardly ever earmarked and therefore are difficult to assess. Moreover, the life span of many measures is not exhausted yet, so that renewal costs data are not reliably available either.

Based on the best estimates available, and using current cost assessment methods, an overall assessment was made comparing the Net Present Value and Equivalent Annual Costs for a range of noise mitigation options. The assessment leads to the firm conclusion that rail freight retrofitting is the preferred option, thus confirming the conclusions from the previous STAIRRS project. The updated graph is presented below. In comparison to the original STAIRRS graph, the number of vehicles to be retrofitted was adapted to the current best estimate (350 000 wagons instead of 710 000 wagons). The cost indicators were changed to Net Present Value instead of the indicator “Present Cost” PCx, which is not as well defined.

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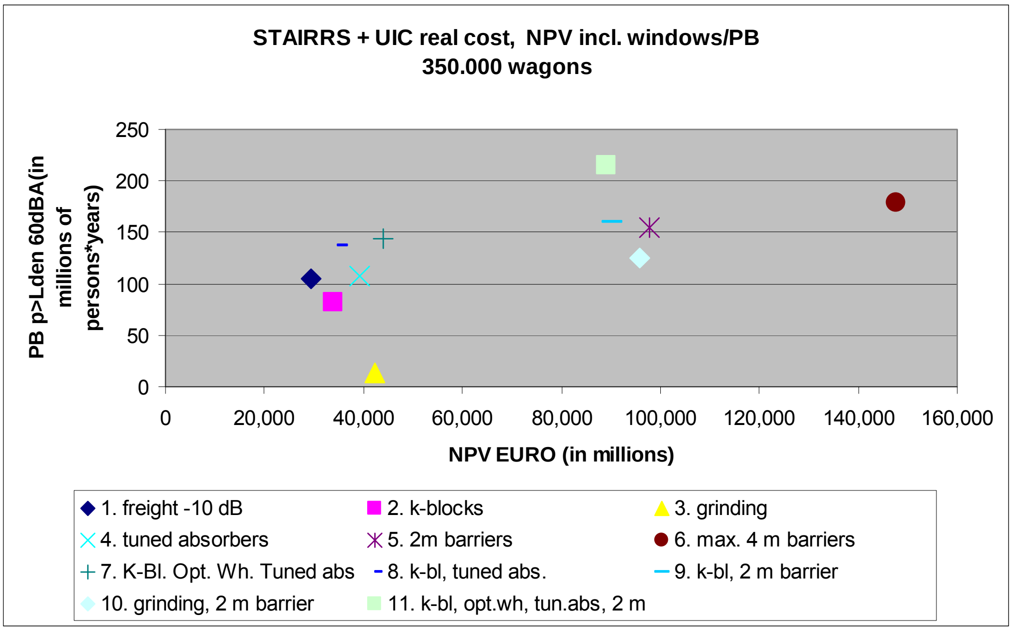

Figure A. Updated STAIRRS cost-benefit figure with NPV instead of PCx, with 350.000 wagons, discount rate 3%.

As can be seen from §6.3, the NPV and EAC of LL-blocks is approx. 25% lower than the values for K-blocks. If we substitute the LL-block NPV into STAIRRS programme 2 (K-blocks), the total NPV will be 25% lower for the figure without window insulation, and 4% lower for the figure with window insulation.

Assuming that the acoustic reduction of K-blocks and LL-block is comparable, this reconfirms that LL-blocks are more cost effective than K-blocks, and that retro fitting as the best option.

1 INTRODUCTION

1.1 Noise and the infra manager: Options for railway noise control

Over the last decade, environmental noise control has become an integral part of the infra managers responsibilities. Although the details of the task strongly depend on the national legislation and national division of responsibilities between the infra manager and the national government, there are key elements in this task that can be found in almost every country in Europe:

Prevention new or extended line	Prevention new dwelling	Sanitation	Voluntary mitigation

1. Compliance with noise reception limits for existing residential areas when a new line or a substantial modification is planned – this element is generally indicated as "prevention".
2. Preventive measures in the case of new residential areas near an existing track. In such cases the initiator of the residential urban planning (i.e. the local government or a private development company) takes the initiative and bears the cost of the noise mitigation measure. When the mitigation measure consists of a noise barrier, often the barrier is erected at the premises of the infra manager. In such a case, the ownership of the barrier is then transferred to the infra manager and some financial compensation is made for its maintenance.
3. Noise mitigation for existing dwellings near existing lines when the noise levels are unacceptably high. Usually this situation refers to the moment in time when national noise legislation has come into force. After all, everything happening after that moment should have been covered by the prevention element. This element is indicated as "sanitation" or "cleaning up".
4. Complaint management, which may give rise to ad hoc mitigation actions in excess of what the legislation requires. This element is indicated as "ad-hoc or voluntary mitigation".

Mitigation of increased noise levels due to traffic growth

The missing element in most of the national legal schemes is the situation where noise levels were within limits at the moment in time when the legislation came into force, but has grown since – usually due to growing traffic flows – into a level that is considered unacceptable, either by the residents themselves or by the local authorities. This element will be regulated once noise emission ceilings will be formally introduced into the legal schemes (this is the case in The Netherlands and Switzerland).
The above elements are illustrated in the following graph. It is assumed that almost all European infra managers are facing all or at least some of these elements.

Whether or not the above tasks need to be carried out depends on the national legislation and the national limit values for noise levels at the façade of dwellings (the so-called immission or reception level). In many countries, two types of limit values have been defined:

- the lower limit, which works as a threshold; below this limit, no measures are required at all and no further assessment is required,
- the upper limit, which should not be exceeded. In case of an excess of this limit, the façade shall be insulated, in order to guarantee a reasonably good acoustic climate inside the dwelling.

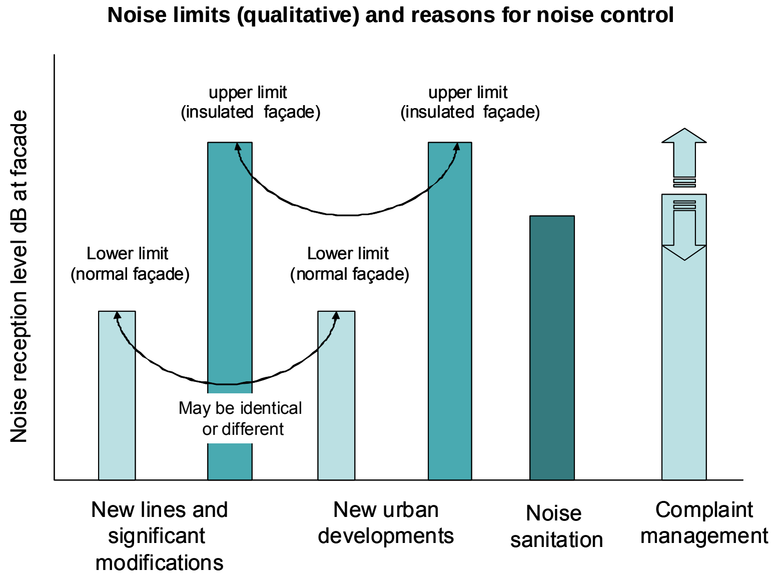

Figure 1-a. 4 reasons for noise control/mitigation and illustration of corresponding limit values

When facing the above requirements, a choice has to be made out of the various options available to mitigate the noise reception at a certain site. These mitigation measures can be categorized as follows:

- Alignment measures, such as increasing the distance (horizontal alignment), cuttings and tunnels (vertical alignment). Usually, noise is only one of several reasons to choose these alignment modifications. They are applied only in the case of new lines or substantial modifications (such as non-level crossings) of existing lines.
- Track measures, such as rail grinding, tuned rail absorbers (dampers), modification of switches, possibly change of sleeper type.
- Vehicle measures. The infra manager may have limited influence to vehicle related measures, for instance through differential track access charges or other operational bonuses and maluses for quiet and noisy vehicles.
- Propagation measures, such as noise barriers and earth berms
- Receiver measures, such as façade insulation, often in conjunction with ventilation measures such as mechanical ventilation.

It is the infra manager's task and responsibility to balance the various options for noise control, preferably to minimize the total cost involved. In order to do so, the infra manager needs to have a realistic impression of the cost involved in the various options. So far, cost benefit optimization was done mainly on the basis of investment cost, ignoring many other important cost elements such as planning and design, maintenance and renewal.
The main cost benefit comparison made frequently is between source related measures, particularly retrofitting the freight fleet, on the one side, and the infrastructure mix on the other. In numerous references, this comparison has been dominated by the well-known STAIRRS graph showing distinct advantages for retrofitting.

At the same time, many efforts have been made to assess retrofitting life cycle cost as accurately as possible. The reason for this was that retrofitting freight wagons with K- or LL-blocks does not only represent the cost for wagon modification and block replacement, but is likely to affect the life span of wheels and blocks. The overall cost of retrofitting can only be usefully assessed with a life cycle approach. This calls for a similar approach for the infrastructure related cost, so that there is a sensible basis for cost comparison. The current study intends to deliver the building stones for such a life cycle cost approach and work these out into recommendations.

Figure 1-b. Options for noise control by the infra manager. Clockwise from top left: alignment (cuttings and tunnels), barriers, façade insulation, track measures (rail absorbers)

It may be a rather novel approach to designate tunnels and cuttings as noise control measures. Indeed, tunnels would never be built in existing lines for noise control reasons only. In new lines, for reasons of noise, ecology, landscaping etc. tunnels may be realized as a means to deal with desires from the surrounding communities. In The Netherlands, a 9 km tunnel was constructed in the new High Speed Line between Amsterdam Schiphol and Rotterdam, mainly for landscaping and environment. Part of the cost for that tunnel can be attributed to noise control measures; thanks to the fact that the tunnel was constructed, noise barriers were not required. The effective noise control cost of that tunnel could be defined as the revenues achieved by avoiding the construction of these barriers.

1.2 Historical review

The introduction and development of rail noise mitigation measures started with track side noise barriers.

Noise barriers

The Euroécran state of the art report [6] gives the following historical overview of noise barriers:

Noise barriers have been introduced in Western Europe as a useful means to reduce community noise as early as approximately 1975. The earliest references on their acoustic efficiency for motorway applications date from 1968. Obviously, their application was heavily promoted by the Noise Control legislation coming into force in different Western European countries (Germany, the Netherlands) by the end of the seventies.

For railway application, noise barriers became even more effective than for motorways, since

- *railway noise is generally emitted from a location close to the track and the wheels of the vehicle;*
- *barriers may be located closer to the source than for motorways.*

Both effects result in a higher efficiency of the barrier.

On the other hand, railways generally experience a higher grade of social acceptance probably thanks to the fact that dose response relations show a lower annoyance with equal equivalent noise level than for motorways. Therefore, noise barriers did not find general application in railways until the railways started to extend their networks.

At that time, noise barriers were mainly vertical plane panels, consisting of aluminum or steel cassettes. The inner surface was acoustically absorptive by means of mineral wool filling and perforated sheet coverage. The height of the barriers was limited to approximately 1.5 meters above R.H. (rail head). One might say that the design of the barrier was at that time mainly dominated by its costs.

Façade insulation

The introduction of sound proof windows started in the late 1970's and early 1980's, particularly in areas where space for new building development was scarce so that dwellings had to be erected close to main infrastructure. Major sound proofing projects have been carried out around airports.

Figure 1-c.
Double glazing with large spacing (from fachwerk.de)

The way of sound proofing depends on many climate and cultural conditions. In the Scandinavian countries, thermal insulation had been present for a long time and only in extremely noisy situations the thermal insulation had to be adapted to supply sufficient noise insulation as well. In the center European countries, sound proof glazing introduced ventilation problems that were solved with either forced ventilation or sound proof natural ventilation. In Germany, Austria and Switzerland double glazing with large spacing stemmed from the traditional architecture. In other countries, gas filled window panes were developed.

In the Nordic and Alpine countries, dwellings may be entirely built out of wood. Such buildings are generally equipped with highly efficient heat insulation. Such buildings hardly ever require any sound proofing at all.

Track measures

Rail dampers and acoustic grinding are developments from the last decade or even last years. Only in very few countries these measures have actually been approved for large scale application.

Alignment
Tunnels and viaducts that are introduced for landscaping purposes may occur in very few countries and for new lines only[1]. Horizontal alignment adjustments may occur for new lines.

Vehicle related measures
In the current report, we focus on rail freight rolling stock, mainly because this rolling stock is by far dominant. Many arguments rose in the current report in relation to the comparison of track related and vehicle related measures may equally refer to passenger rolling stock. The vehicle related measures for the existing freight and passenger fleets look quite different. Whereas retrofitting the brake system would be the preferred measure for freight cars, modern passenger stock hardly ever has brake systems other than disk brakes. Noise reduction for passenger stock would require wheel dampers, shrouds, and silencing the traction and auxiliary machinery. Such measures are not addressed in the current report.

In 1998, UIC, in collaboration with Unife and UIP, launched the Noise Action Program, focused on the development of alternative brake blocks for freight wagons. The program was based on the notion that retrofitting the freight fleet is the most cost efficient mitigation measure for railway noise. This notion was based, among others, on the results and conclusions of the STAIRRS project. It clearly indicated that the community cost involved with the erection of noise barriers and the installation of façade insulation were much higher than the cost involved in retrofitting the freight fleet, assuming that these costs would be covered by public resources.
Since 1998, the majority of the European passenger fleet has been equipped with disk brakes due to renewal of the fleets. This makes these trains relatively quiet. On mixed lines, where freight traffic is taking place mostly during the night, and on dedicated freight lines, retrofitting remains the preferred option. Two main issues have been in the way of this process: discussions about the financing of this retrofitting operation, and the lacking homologation of LL-type brake blocks, which would represent the more cost efficient way of retrofitting compared to retrofitting with K-blocks.

Comparability of alternative measures
The basis for comparison between the different mitigation options is the reduction of the noise level at the façade that can be achieved by that measure. The assumption is that any reduction, equal in dB difference compared to the reference situation, has equal effect to the residents under concern. This however is questionable, for the following reasons:

- for vehicle related measures, the impact on the residents may be noticeable only when a sufficiently large percentage of all the vehicles passing his dwelling are treated,
- for barriers, the positive impact of a reduced noise exposure are partly compensated by the negative impact of the intrusion on his view and the sensation of being cut off from the opposite side of the track caused by the barrier,
- for façade insulation, the reduction occurs inside the house only. Noise exposure in the garden and on balconies would not be present, and the positive effect on annoyance therefore is less than for a vehicle or propagation related measure with the same noise level reduction.

In addition to the above, some of the measures described are suitable for new lines and/or extended lines only, whereas other measures can be applied to an existing line as well. This also leads to a situation where one measure cannot be simply compared to a different measure with similar noise reduction.

[1] For example in The Netherlands, where a 9 km tunnel was introduced in the new high speed line, for landscaping purposes only

2 LIFE CYCLE COST ASSESSMENT

A fair comparison of the pros and cons of each noise mitigation measure is only feasible, if sufficient cost information is available. That has been an issue in the recent past. A range of different studies has been dedicated to the assessment of the cost of noise control measures. For instance, in the early 1990-ies, UIC participated in the EC funded project Euroécran, which – among others – assessed the installation cost of different types of noise barriers.
Recent regulations which were intended to reimburse the cost using budgets provided by the national government are based on estimates for the investment cost of such measures. However, there are distinct problems in assessing this cost with sufficient accuracy, the most significant of these problems being:

1. For innovative solutions such as rail dampers, the number of suppliers increases rapidly once the end user accepts these products. This affects the price rapidly, so that estimates tend to be outdated soon.
2. Maintenance differs drastically from one infra manager to another, due to local and regional habits and strategies. For instance, the cleaning strategy and the cleaning attitude of graffiti from noise barriers differs enormously from one infra manager to another, and therefore the cost for cleaning will differ as well.
3. Depending on the accountancy system maintained by the infra manager under concern, the cost is not adequately earmarked and cannot be assessed from easily accessible sources such as the annual report.
4. Many noise reducing devices may have life spans of 30 years or longer. They have not existed long enough yet to assess the life cycle cost from practical data, simply because they have not yet reached the end of their life span. This applies to some types of noise barriers, but also to elements of façade insulation such as window frames.

Particularly the latter situation obviously improves over time. Assuming that noise barriers and sound proof façades have been installed since the late 1970-ies, gradually replacements and renewals take place, so that a full life cycle cost assessment can currently be based on at least one full life cycle. For tunnels and cuttings, only part of the cost can be allocated to noise, as these provisions serve other purposes than only noise control. For track related measures, the information about the life cycle of rail dampers is poor, but information about the frequency of (acoustic) rail grinding and the life span of different sleeper types should be available without problems.

This means that the time is right to improve earlier cost assessments that were based on estimates and expectations, and replace these figures by real data from practice.

2.1 Objectives of the study

According to the Terms of Reference, the overall aim of the study is to

> ***support the infrastructure manager's awareness of maintenance and replacement costs of existing noise mitigation measures.***

To this effect, the project should

> ***gather 20 years of real experience with maintenance cost on the most frequently used noise measures (noise barriers, insulation of buildings, track***

absorbers and acoustic rail grinding), to analyze the replacement costs of noise mitigation measures and hereafter to analyze the financial risks involved.

In the above introduction, we have added alignment measures, which can at least partly be attributed to noise control. The issue has proven to be provoking discussions which sometimes disturb the real purpose of this study. We will therefore touch upon the issue of alignment measures only briefly.

2.2 Methodology

In this project the following methodology was used:

1. Parallel development of a lifecycle cost (LCC) model and a questionnaire to collect data to be fed into this LCC model
2. Distribution and collection of the Questionnaire including follow-up for better response
3. In case of missing data, application of alternative approach
4. LCC analysis per country and for all EU countries together for existing and planned measures
5. conversion of LCC cost to NPV/unit measure
6. Update STAIRRS cost-benefit figure with NPV per unit measure

2.3 Glossary of Terms and Symbols

The following table presents some of the terms applied in this study with their definitions.

Table 1. Glossary of terms

Net Present Value (NPV)	the sum of the discounted future cash flows, both costs and benefits/revenues.
Net Present Cost (NPC)	the sum of the discounted future cash flows, costs only
Life Cycle	The defined service life cycle of the constructed asset, shall be the period of time between the inception and completion of the functional need (which maybe cradle to grave)
Life Cycle Cost (LCC)	the cost of an asset, or its part throughout its cycle life, while fulfilling the performance requirements. costs are those associated directly with constructing, operating and disposal
Total Ownership Cost (TOC)	LCC + linked indirect fixes costs
Whole life Cost (WLC)	TOC + non linked indirect fixed cost
linked indirect fixed costs	Cost for functioning of measure: planning, administration, supervision
non linked indirect fixed cost	Cost for organization: office building, staff.
Discount Rate	time value of money that is used to convert cash flows occurring at different times to a common time
Period of Analysis	Length of time over which an LCC assessment is analyzed.
Equivalent Annual Costs (EAC)	Cost per year of owning and operating assets over their entire life span
STAIRRS	Strategies and Tools to Assess and Implement noise Reducing measures for Railway Systems
Eurano	European Railway Noise software developed for STAIRRS

3 THE ART OF ECONOMICS

A full version of this chapter is included in Annex 1.

Discounting is a widely used technique for comparing costs and revenues occurring at different points in time on a common basis, normally the present time. It is based on the principle that a sum of money to hand at the present time has a higher value than the same sum to hand at a future date, because of the earning power of that sum in the interim.

The generic formula for calculation of the Net Present Value (NPV) by discounting is shown in equation (1):

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \qquad (1)$$

where

NPV = Net present value
C_t = Cost of item t
r = discount rate
T = analysis period in years.

The total NPV for a measure includes operation costs, maintenance costs, replacement costs, and residual values / disposal costs:

$$NPV = I + A + C + D - S \qquad (2)$$

where

I = initial or investment cost
A = the present value of annually recurring operating, maintenance and repair cost
C = the present value of non-annually recurring operating, maintenance and repair cost
D = the present value of disposal/replacement costs
S = the present resale value

A representation of these lifecycle costs for one lifecycle is given in Figure 3-a.

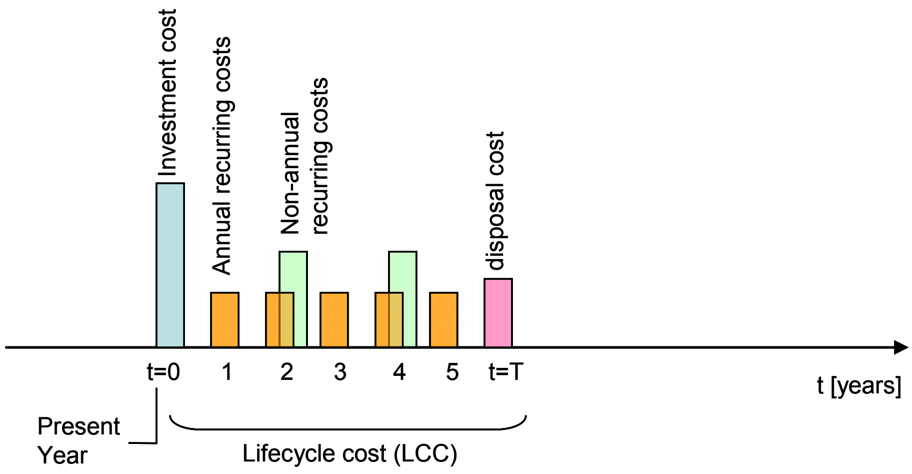

Figure 3-a. Lifecycle costs for one lifecycle

Kishk and Al-Hajj (2000) [2] developed a life cycle costing model. In this model, the discount factors for annual costs and non-annual costs are formulated for simplifying the time and effort required in the computation process.

The NPV can be shifted in time by applying the present worth factor (PWS) to the lifecycle costs (Figure 3-b):

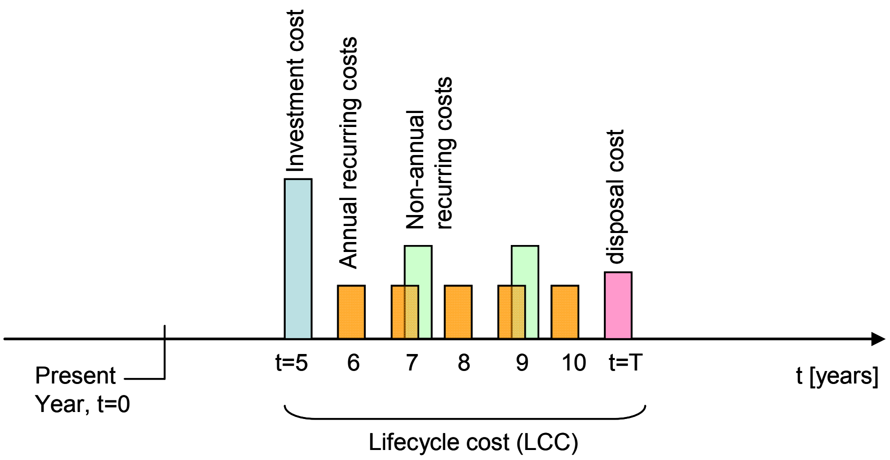

Figure 3-b. Lifecycle costs for one lifecycle shifted in time

Several lifecycles can be “linked” into a chain in time to calculate the long term lifecycle costs. With as the TP as total long term analysis period and $t_1 \ldots . t_x =$ year at start of each lifecycle (Figure 3-c).

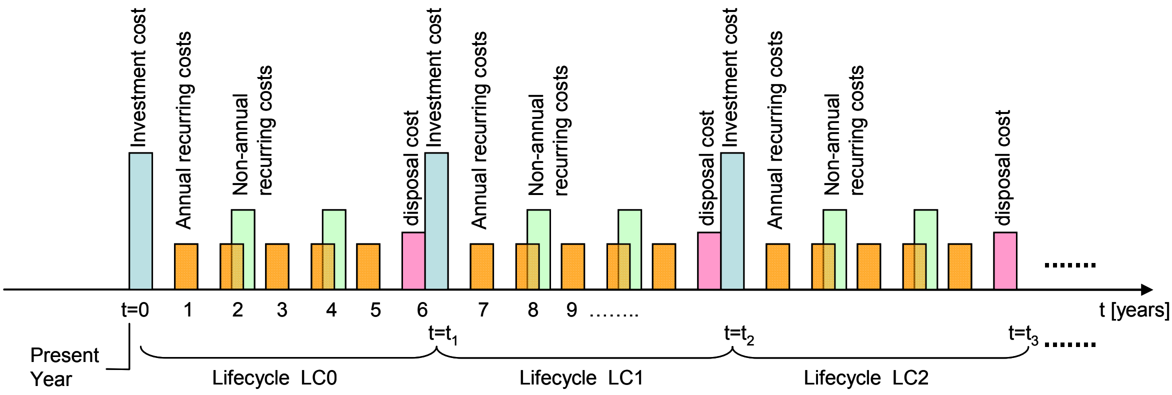

Figure 3-c. Lifecycle costs for several lifecycles in a row

Rather than being expressed as a one-time net present value, a method is available to convert all costs of a measure into a uniform equivalent annual cost (EAC)[5]. The EAC of measure *i* is related to the NPV of measure i by the PWA factor as follows:

$$EAC_i = \frac{NPV_i}{PWA_i} \qquad (3)$$

Where

EAC_i = Equivalent Annual Costs of measure i
NPV_i = Net present value of measure *i* in present year t=0, from formula

The big advantage of using EAC is that calculation of the EAC can be simplified to one lifecycle.

4 ASSUMED INPUT VALUES

4.1 Discount rate

There are two possible approaches to dealing with inflation in relation to discount rate:

- ‘nominal’ discount rate: a rate that is not adjusted to remove the effects of actual or expected inflation. This means that inflation predictions are built into forecast costs and prices
- ‘real’ discount rate: a rate that has been adjusted to remove the effect of actual or expected inflation. This means that future costs and prices are estimated at present day (‘real’) prices and inflation can be dealt with separately.

If inflation rates for all costs in the analysis are approximately equal, it is common practice to use a real discount rate and therefore exclude inflation from the LCC analysis.

Selecting an appropriate discount rate is critical for a LCC analysis. In practice rates can vary widely. Key considerations are the cost of capital, the perceived level of project risk and the opportunity cost of capital (i.e. the level of return that could be generated by investing the capital elsewhere).

National ministries of finance in the public sector generally specify the discount rates in the range of 3 to 5% to be used in the economic analysis of publicly funded projects[1].

4.2 Network length

Network length is gathered from different sources [3,4,a,b], where *UIC report Noise Reduction in European Railway Infrastructure*[3] is the primary source.

EU Member States / EFTA countries	Code	Network length [km]	Existing measures
Austria	AT	5690	yes
Belgium	BE	3536	yes
Bulgaria	BG	4294	-
Cyprus	CY	0	-
Czech Republic	CZ	9513	yes
Denmark	DK	2323	yes
Estonia	EE	1200	-
Finland	FI	5850	yes
France	FR	32000	yes
Germany	DE	34218	yes
Greece	EL	2571	-
Hungary	HU	7729	-
Ireland	IE	3312	-
Italy	IT	16225	yes
Latvia	LV	2347	-
Lithuania	LT	1998	-

EU Member States / EFTA countries	Code	Network length [km]	Existing measures
Luxembourg	LU	274	-
Malta	MT	0	-
Netherlands	NL	2806	yes
Poland	PL	19507	yes
Portugal	PT	2800	yes
Romania	RO	11385	-
Slovakia	SK	3668	-
Slovenia	SI	1202	-
Spain	ES	12814	yes
Sweden	SE	10000	yes
United Kingdom	UK	16116	yes
Switzerland	CH	5035	yes
Norway	NO	4087	yes

Table 2. EU27 states + Switzerland and Norway (European Free Trade Association (EFTA) , country codes and network length [3,4,a,b]

In *EU transport in figures, Statistical pocketbook 2011* [16] *section 2.5.3. : Railways Length of Lines in Use*, the railway network in the EU's 27 member countries is shown to have shrunk by 2.2% in the last 10 years, with a percentage ranging from ±0-3% for most member countries, and some higher: Spain (+ 8.5%), Italy (+5.0%) and Belgium (+ 3.1%). In general no big rail infrastructure projects are expected in the near future.

Therefore, network growth is assumed to be 1% of the existing network length over 20 years. Growth is taken as default growth of 1% over 20 years, unless country specific data was available. The assumed percentage of growth is used in the current study to assess the costs associated with noise mitigation for new and “significantly modified” lines. The overall costs are only marginally affected by the growth range, because many noise mitigation costs are associated with noise cleaning up or new spatial developments rather than new lines.

4.3 Measures

As presented in section 1.1 several options for controlling railway noise are available:

- Alignment measures
- Track measures
- Vehicle measures
- Propagation measures
- Receiver measures

Background and application of these measures are explained in the next section.

4.3.1 Alignment measures

So far, alignment measures have not been investigated. Given the difficulties encountered in collecting data on noise barriers in the various countries, we have excluded this subject from the analysis.

It is assumed that tunnels and viaducts are not generally constructed for noise reasons only. Part of their cost however could be attributed to noise as they represent avoided cost for noise barriers. As the decision for their realization is not likely to be based on noise control objectives, the avoidance cost represent a basic and significant cost element in the total cost calculation for a mix of mitigation measures.
In the comparison the cost for alignment measures however are not discriminative, so there they can be left out without affecting the overall conclusions.

4.3.2 Track measures

track absorbers/rail dampers
Rails and sleepers are emitting noise. The transmission of vibration energy to the sleepers depends on the stiffness of the rail fixation. The stiffness of the fixation also controls the track decay rate, i.e. the decay of vibration energy along the length of the rail from the point of excitation (i.e. where wheel and rail touch each other). The track decay rate can be optimized by using stiff rail pads and/or by using rail dampers. Whereas the choice of rail pads is made in the general track design, i.e. during the planning phase of a track, rail dampers can be added to an existing track as a mitigation measure. Therefore, we concentrate on rail dampers instead of stiff rail pads.

In the Netherlands two makes of rail dampers have gained national approval for heavy rail application and are currently applied in practice. These are supplied by Corus (currently Tata Steel) and by S&V respectively. The report *Kostenkengetallen raildempers en schermen ProRail* [8] gives LCC costs for these two types of rail dampers. The final effect depends on several parameters like track decay rate (or rail pad stiffness), rail roughness, and the type of traffic. Therefore the reported efficiency of rail dampers shows a high variation.

acoustic rail grinding
Rail grinding is a proven technology to remove heavy rail corrugation which affects passenger comfort and may introduce track damage. Such heavy rail corrugation can generate high pass by noise levels, sometimes even up to 15 dB higher than with good quality track. Rail grinding is applied in many networks and could reduce local noise levels significantly, but the primary reason for grinding usually is not noise control. In this study we assume a reference of good quality track throughout the network. Heavy rail corrugation is considered an a-typical incident.
In addition to this type of grinding, acoustic grinding has been introduced in Germany in the last decade. Acoustic grinding has been developed to improve the acoustic performance of a line. Acoustic grinding includes periodic real time monitoring of the track roughness, followed by low roughness grinding for the locations where a threshold value is exceeded. This procedure is called “especially monitored track” (besonders überwachtes Gleis). In the German legal prediction scheme, a 3 dB reduction can be included for any especially monitored track. The actual cost of the grinding itself, as well as the total length of track that has been treated, should be easy to assess. But rail grinding, including acoustic grinding, is likely to affect the life span of the rail itself. Some will argue, that rail grinding takes away material from the rail head and would therefore shorten the life span. Others however would argue that acoustic grinding would prevent rail corrugation growth and would therefore lengthen the life span of the rail. Probably less than 10 years of experience is too short to assess these effects with sufficient accuracy, and therefore cost assessment of acoustic rail grinding is still controversial. Acoustic rail grinding is therefore not included as an alternative in the current report.

4.3.3 Vehicle measures

Rolling noise is the result of roughness on both the wheel and the track. If both wheel and track are smooth a significant part of the noise is eliminated. Smooth wheels can be achieved with composite or sinter metal brake blocks. The so-called retrofitting of the freight fleet includes replacing the conventional cast iron brake blocks with composite or sinter metal blocks. Two types are distinguished: K-blocks and LL-blocks. LL-blocks simulate the friction coefficient of cast iron brake blocks, and therefore only minor adaptations to the brake system are requested when replacing conventional cast iron blocks with LL-bocks. K-blocks have a highly different friction coefficient compared with cast iron brake blocks, therefore they require a significant modification of the brake system and thus K-blocks are more expensive to apply on existing vehicles.
K-blocks have been homologated for general application for a long time, but in spite of many efforts for several decades, LL blocks have not received general approval yet.

In 2002 the Dutch Ministry of Transport, Public Works and Water Management (V&W) started the Noise Innovation Programme (Innovatie Programma Geluid = IPG). One of the programme' s (sub)-goals was to determine the influence of LL-blocks on the LCC of a freight wagon. The results of this LCC were given in report *The Whispering Train Programme - Life Cycle Cost Calculation* [12], and *Geluidspilot Dolomiet-shuttle, Life Cycle Costs analyze voor het Innovatie Programma Geluid* [15].

Type	Retrofitting cost (investment)	Additional LCC cost/year	Lifecycle [year]
K-blocks	7.000 - 9.000 €	300 €	40
LL-block	2.100 €	400 €	40
Wheel absorbers	27.000 €	400 €	20

Table 3. Average cost of retrofitting with composite LL-blocks in the Netherlands, based on an annual mileage of 50 000 km adapted to a 4-axle wagon.

The estimated number of freight wagons to be retrofitted in Europe is 350.000 wagons. At present approx. 20.000 wagons have been equipped with K-blocks. These are the result of the Swiss retrofitting program and of some fleet renewal that has taken place over the last decade. Wagons with insufficient rest life or insufficient annual mileage will not be retrofitted.

4.3.4 Propagation measures: noise barriers

In the EUROECRAN project[6] a barrier categorization system was set up to be able to compare current barriers of a same kind. Barriers can be distinguished in three ways: the shape, the main material and the sound absorption method, see Annex 9.
To simplify the input for the questionnaire, the list of barriers is reduced to a main list by material type:

- Concrete barriers: reflective
- Concrete barriers: absorptive
- Metal box barriers: absorptive
- Transparent barrier: glass, acrylate
- Timber barriers
- Green barrier with plants
- Earth bank

This classification of barriers is used in the Questionnaire. In case this data is difficult to obtain, the Questionnaire contains an option to fill out the total amount of barriers.

Figure 4-a. Metal box barrier alongside a railway line

4.3.5 Façade measures

If noise levels in residential areas are very high measures at the receiver may be required, implemented as adjustments to houses. Depending on the national legislation and the functional purpose of rooms in those houses maximum interior noise levels may be required varying from approximately 28 to 43 dB.

The type of façade measures depends on the quality of the building, which is linked to national tradition. In the Nordic countries, many houses, particularly in rural sites, are made of wood and very heavily heat insulated. Acoustic insulation is usually not needed. In middle European countries, buildings would be constructed from concrete or brick, and windows would be the “weak points” from an acoustic point of view. In traditional southern European houses, windows would be usually open, and insulation would not bring any benefit. In modern buildings throughout Europe, forced ventilation may become more common, and there are good opportunities for high quality soundproofing of the windows. For the purpose of this report, we assume window insulation as the common receiver option.

The type of receiver measures required depends on the difference between the noise levels outside and the required interior noise level in the rooms. Without special measures, the sound insulation of a façade of a house is generally at least around 18 dB. If a higher reduction in noise level is needed to reach the required interior noise levels, additional façade measures will have to be taken. There are various types of façade measure available. The most important are:

- Window insulation (double glazing)
- Noise sealing of window frames
- Noise insulated window ventilation systems
- Measures for roof insulation
- Measures for light weight panels in the façade

Each type has its own effect on the sound insulation and thus on the noise reduction to be reached. Various categories of achievable noise reduction can be distinguished:

- To increase the achievable noise reduction of a façade from approximately **18 up to 22 dB** the windows in the façade will have to be equipped with sound proof ventilation systems.
- To increase the achievable noise reduction of a façade further **up to 24 dB** double glazing (requiring new moveable windows), noise sealing of the window frames, and sometimes simple roof insulation will have to be installed in addition to the noise insulated window ventilation system.

- To increase the achievable noise reduction even further **up to 26 dB** the double glazing will have to be thicker/heavier (now also requiring new fixed windows) and the roof insulation will have to be more extensive.

Each of these steps has a significant influence on the total costs for implementation of the façade measures. The achievable noise reduction can be increased even further than 26 dB by using better (thicker, gas filled, coated etc.) double glazing and more extensive roof insulation. The influence on the costs will however be smaller than the “cost jumps” made in the above mentioned categories. In this study therefore the following categories are distinguished for the required noise reduction of a façade:

- 18 to 22 dB
- 22 to 24 dB
- > 24 dB

The average costs for the measures required for each of these categories are also strongly influenced by the dwelling type. The costs for noise insulation measures in a certain noise reduction category will be much lower for a home in a multi-story building than would be the case for a villa. In Table 4 an overview is given of the noise insulation measures required for the various noise reduction categories and average costs of these measures taking into account various dwelling types.

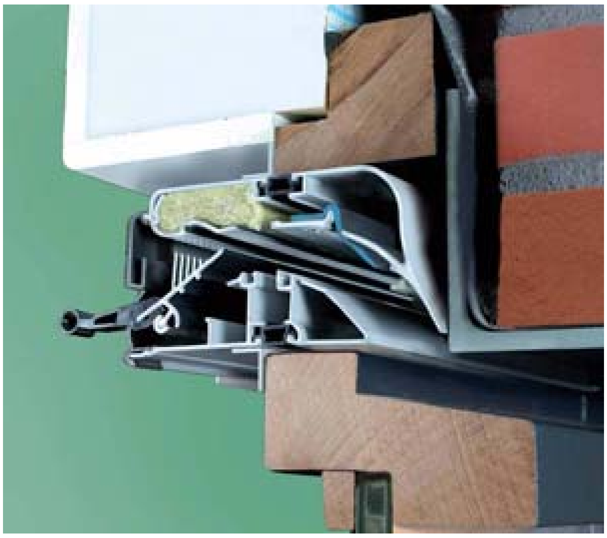

Figure 4-b. Example of sound proof ventilation system (source: http://bve.sco.cf.noordhoff.nl/)

	Noise reduction category: Required noise reduction in dB		
	18 – 22 dB	***22 – 24 dB***	***> 24 dB***
Properties	o noise insulated window ventilation systems	o noise insulated window ventilation systems o double glazing o new moveable windows o noise sealing of the window frames o simple roof insulation	o noise insulated window ventilation systems o thicker double glazing o new moveable windows o new fixed windows o noise sealing of the window frames o more extensive roof insulation
Cost for home in multi-story building	€ 700	€ 3500	€ 5000
Costs for terraced homes	€ 1400	€ 8000	€ 14000
Costs for detached homes	**€ 2000**	**€ 15000**	**€ 26000**
Costs for villas	€ 4000	€ 30000	€ 52000

Table 4. Overview of properties and costs in the Netherlands of the 3 noise reduction categories for various dwelling types

To simplify the input for the questionnaire the costs for detached homes are used as first estimate for the general costs required for noise reduction measures for various dwelling types.

No costs are taken into account for yearly maintenance. For the double glazing, windows, window ventilation systems and insulated roofs no additional maintenance is required in comparison to the situation when standard materials are made. So no additional maintenance costs will have to be taken into account for noise insulating receiver measures.

For non-annual costs replacement of the measures should be taken into account. The noise insulated window ventilation system and the noise sealing of the window frames should be replaced every 20 years. For the windows and the roofs a lifetime of 50 years should be taken into account. This results in the following replacement costs for the 3 noise reduction categories:

- 18 to 22 dB: € 2000,- every 20 years
  € 0,- every 50 years
- 22 to 24 dB: € 9500,- every 20 years
  € 5500,- every 50 years
- > 24 dB: € 12000,- every 20 years
  € 14000,- every 50 years

For disposal costs 5 % of the purchase costs can be taken into account as indication.

The resale value of the materials after removal can be neglected. For the questionnaire the resale value can be set to zero.

In case the costs for renewal of façade insulation is considered not to be the responsibility of the railway, a sensitivity analysis is carried out to calculate the effect of taking only into account the investment costs. The results of this sensitivity analysis are given in §6.2. The effect of renewal of façade insulation in the total LCC is less than 1%.

5 THE QUESTIONNAIRE

The questionnaire was sent to a group of railway noise related experts in the various countries. In general, we strived for a positive response (i.e. there is actual data available and it is made available to us) in the order of 40% for the questionnaire. The final selection of experts was based on the countries where we expect a major investment in noise control, e.g. Germany, The Netherlands, Switzerland, Austria and Italy (see Table 2). The final selection for distribution is also based on the analysis of the 2007 CER/UIC report “Noise reduction in European railway infrastructure”. The current study partly builds on this previous work.

The questionnaire basically consists of three main blocks, viz. amount of measures, LC Costs and network information for existing and planned tracks.

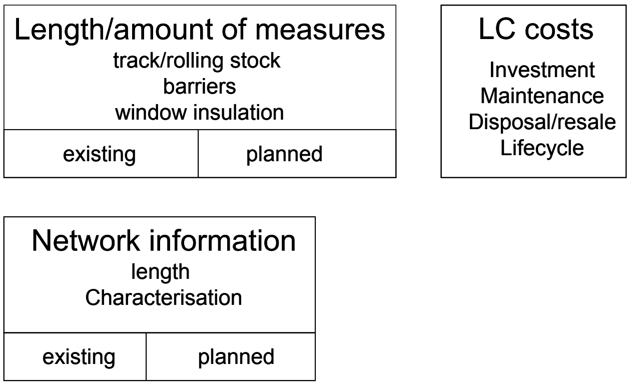

Figure 5-a. building blocks of the questionnaire

5.1 Distribution and content

The questionnaire was distributed to the contact points by e-mail in January 2012. The questionnaire contained an Excel form and a letter (see Annex 2) with explanation of the questionnaire and the aim of the project. An e-mail alert was sent in February 2012 and after this, every contact point was offered personal assistance with filling out the questionnaire. A second round of consultation was held in April 2012. Correspondence is given in Annex 5.

Country code	contact	Round 1/ send	Round 1/ received	Received from:	Round 2 / received
AU	M. Bukovnik	30-1-2012			
BE	E. Verhelst	16-1-2012			
CZ	H. Lavacekj	16-1-2012			
DE	R. Garburg	16-1-2012	1-4-2012	F.Goecmen	11-4-2012
DK		16-1-2012			
ES	M. Rodriguez	16-1-2012		I. Aspuru	12-5-2012
FR	C. Martin F. Poisson E. Bongini A. Guerrero	16-1-2012			

	N. Vinciguerra				
FI	E. Poikolainen	16-1-2012			25-4-2012
HU	Kancsalicse	16-1-2012			24-4-2012
IT	E. Lucadamo I. Ricciardi	16-1-2012			
NL	DHV / ProRail	1-1-2012	1-1-2012	DHV / ProRail	11-4-2012
UK	S. Topping	16-1-2012	27-2-2012	N. Craven	16-4-2012
CH	R. Attinger	16-1-2012		R. Attinger	11-4-2012
NO	T. Borsting	16-1-2012	1-2-2012	R.G. Simonsen	16-4-2012

Table 5. contact points for questionnaire. Grey records: no response received

The Excel-questionnaire (see Annex 3) contains 5 input tabs: general information, contact information, existing measures, planned measures and distribution and noise limits. It also contains a tab for LCC analysis.

5.2 Data collected

5.2.1 The Netherlands

The data for the Netherlands was collected from several resources. LCC costs for barrier- and rail damper measures come from the report *Kostenkengetallen raildempers en schermen ProRail* [8], enriched with specific data from DHV. LCC Costs for receiver measures are based on several sources from ProRail and DHV.

The Dutch LCC costs are used as default costs for other countries, if these costs are not specified in the Questionnaire.

In the Netherlands, knowledge about LCC Costs for measures is evolving. During the time of writing of this report a LCC study for ProRail was published, *PRO027-02-07ew_IJking doelmatigheidscriterium voor spoorwegen aan nieuwe normkosten* [17]. Average LCC costs for barriers higher then 2m differ less then 2% from the LCC costs used in this research, giving a difference in NPV/EAC of approx. 3%.
In the study *PRO027-02-07ew_IJking doelmatigheidscriterium voor spoorwegen aan nieuwe normkosten* [17] average LCC costs for track absorbers differ mainly in yearly maintenance costs, up to 6 times higher then used in this research (average initial costs are 5% higher). The exact costs breakdown of yearly maintenance costs is not given, therefore it is difficult to compare NPV/EAC costs with this research.

The amount of existing noise barriers by type and rail dampers comes from the national emission register ASWIN (Akoestisch Spoorboekje or “acoustical timetable”) [11]. The total length of noise barriers is approx. 420 km in 2011.

The amount of existing and future receiver measures is taken from the national sanitation list for railways, and from the report *Samenvoegen saneringsbudgetten van VROM en VenW voor geluidreductie spoorwegen Eindrapportage Y-onderzoek* [9]. In this last report the threshold is 70dB L_{den} and the preferred noise limit is 65dB L_{den}.

Estimation of the number of existing and planned retrofitted freight wagons (for Dutch wagons only) is based on the report *Bevordering Implementatie Omloopstudie goederen* [13]. Cost are taken from the report *The Whispering Train Programme - Life Cycle Cost Calculation* [12]. This information was gathered for background only. In the comparison, we will use numbers of wagons for the whole of Europe only.

With these datasets the existing and planned measures are estimated. New planned network length is estimated on 10% of total existing network length.

5.2.2 Norway

The questionnaire received from Norway contains total length of existing and planned noise barriers and track absorbers, and total amount for existing and planned houses with window insulation.
LCC figures were not filled out.

5.2.3 UK

Information from the UK was received by e-mail. With this information the questionnaire was filled out by DHV.

Use of cast iron brake blocks is rare in GB and the UK does not have issues with retro-fitting, or scrapping of wagons. There are only a few instances where wheel absorbers have been used and there is no acoustic grinding on the main network.

By comparison to mainland Europe the UK has relatively few noise barriers. These tend to be installed for new infrastructure only or where lines are modified or upgraded. The design and installation are covered by individual projects, making it difficult to collate figures or generalize about design and costs. There is no specific budget for on-going maintenance of barriers. The following estimates are made for investment costs:

Barrier 2 meters high = £900 per meter length
Barrier 3 meters high= £1275 per meter length
Barrier 4 meters high= £1650 per meter length

Similarly, secondary glazing is only installed for new or upgraded infrastructure projects where other forms of mitigation are not practicable. A cost estimate of about £3,000 per window was used for the Thames link project, but this is for a small number of windows in old (listed) buildings and so not typical or representative. The expectation is that average costs for larger projects might be significantly lower perhaps £3000 per building. The majority of installations would be 'light' as defined in the questionnaire. Once installed the maintenance costs are assumed by the building owner.

There is an estimated budget of £10 to 20 million for the period 2014 to 2019 to cover noise mitigation in response to the environmental noise directive. This is the first time there will be a nationwide noise mitigation programme, but this has not yet been approved. At the moment the expectation is:

70% rail-tuned absorbers
5% single-side barriers
5% double side barriers
10% sound insulation
10% bridge noise reduction

From this budget the amount of measures until 2020 was estimated.

5.2.4 Hungary

Hungary has no data available. an estimate was made based on the alternative approach described in §5.3.

5.2.5 Finland

Buildings in Finland: because of cold climate all buildings have double glazing windows as a minimum, so average window insulation is about 20-25 dB in the whole Finland. Starting in the 1970-ties most of the

Finnish buildings have 3-glass windows and some even 4-glass windows, so in some houses window insulation goes as high as 35-40 dB.

Retrofitting: The Finnish freight fleet does not require retrofitting because it has wide gauge. It is not subject to the UIC noise action plan.

The Finnish traffic agency is making a database of noise barriers, but work is still going on and they only can give a good guess of the total length of noise barriers. Maybe next year (2013) the national database covers more than 90 % of barriers. A good guess is 50-60 km of current rail noise barriers.

Most of the Finnish rail network consists of mixed lines, because about 90% of the network is single line.

Newly planned network: in the Helsinki area the so called Kehärata is planned, with a total length of about 15 km. It will be finished in the year 2014. In the northern part of Finland some new railway lines are under discussion because of the mining industry.

Track absorbers: track absorbers have been tested, but the test results were unsatisfactory, therefore there are no plans to use them in the near future.

5.2.6 Spain

In Spain most of the noise measures are planned in the context of the implementation of the Directive or in the new network for High Speed Line. The Action Plan 2008 gives some information about noise barriers:

- There is a global strategy about their height. A maximum height of 4 m was fixed. Some exceptions are allowed, but only if the increase in height means that the whole affected building would be protected.
- On viaducts, the maximum height is set at 2 m, without any exception.
- Every noise barrier less than 3 m height would have absorption properties.

The Action Plans also mention acoustic rail absorbers as a measure. The action plans only identify the areas with problems and which of them could be solved by installing a noise barrier.

The dimensions of the noise barriers are not defined, but a global budget of 109.162.950,00 € was set for future measures.
Special studies for High Speed Lines generated the following cost for noise barriers:

- Concrete absorbing noise barrier: material 75 €/m2 and installing 115 €/m2.
- Metal absorbing noise barrier: material 113 €/m2 and installing 130 €/m2.
- Transparent (methacrylate) noise barrier: material 83 €/m2 and installing 145 €/m2.

With the above figures, the average investment cost are: 210 €/m2
With the global budget as mentioned this equals approx. 130 km of 4 m high barriers.

5.2.7 Switzerland

The questionnaire received from Switzerland contains total length of existing and planned noise barriers and track absorbers, and total amount for existing and planned houses with window insulation.
LCC figures were filled out for investment costs. Other lifecycle costs were estimated from the Dutch cost figures (default method for missing data, see §5.3.

5.2.8 Other Countries

Other countries did not respond. For these countries an estimate was made based on the alternative approach described in §5.3.

5.3 Alternative approach to the questionnaire

An alternative approach was developed in case of a low final response to the questionnaire. From experience with the questionnaire our conclusion is that:

- Collection of LC Costs is complicated. The LCC research available in the Netherlands is not obvious for other countries and is/might be difficult to obtain
- Estimation of existing and planned measures is not easy either, where estimation of planned measures is more difficult than existing measures

In case of a low final response on the questionnaire the following approach was used to fill in the data not provided in the questionnaire:

- If LCC costs are missing in the questionnaire, take the Dutch LCC cost multiplied by the Comparative price index NL=1 (see Annex 4).
- If planned network length is missing, take 1% of existing network length
- If length and amount of measures are missing, take measures from UIC status report 2007 [3] and modify these figures by expert judgment

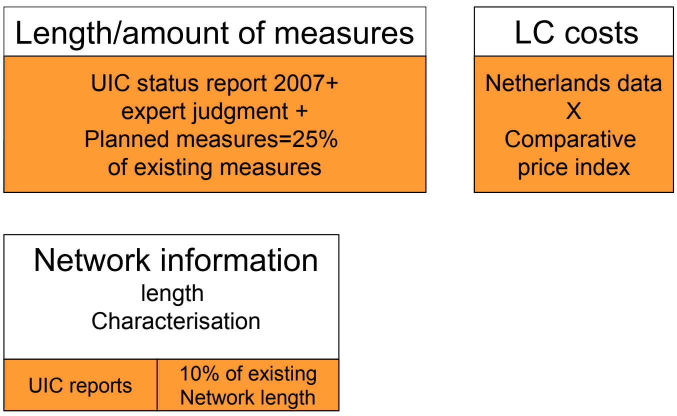

Figure 5-b. Alternative data for building blocks of the questionnaire

In addition, END action plans were studied. The END action plans are generally too global to be used in this survey.

5.4 Aggregated data: UIC questionnaire compared to UIC 2007 data

Table 6 presents the aggregated data collected with the questionnaire for the total length of noise barriers/track absorbers and housed with window insulation. The figures from the UIC 2007 report [3] are added for comparison.

UIC questionnaire 2012									UIC Status report 2007 [3]			
Country code	Rolling stock [wagons]		Track absorbers [km]		Barriers [km]		Window insulation [houses]		Barriers [km] 2005		Window insulation [houses] 2005	
	ex	pl	ex	pl	ex	pl	ex	pl	ex	pl	ex	pl
BE					120	30	4000	2000	86	-	0	0
CZ					115	15	1500	1500	-	-	-	-
DE		1250	140		1050	300	46000	10000	167	-	27600	-
DK				10	70	20	10000	6500	58	-	7486	3000
ES				10	150	130	3000	2000	-	700	-	-
FR			50	50	300	30	10000	5000	2	-	-	-
FI					60	10	4000	3000	-	-	-	-
HU					50	10	1500	1000	-	-	-	-
IT			20	50	50	500	8000	8000	5	700	0	0
NL	1000	15000	99.1	450	420	1100	14347	10000	200	-	-	-
UK				28	5	33	0	500	-	-	-	-
CH	7512	1834		20	348	113	24389	61300	33	149	3000	3300
NO			0.5		50	10	100	200	-	-	150	-
AT			20.0		450	50	2000	1000	295	-	1550	760

Table 6. Aggregated results from the questionnaire, compared to data collected in the UIC-report *Noise Reduction in European Railway Infrastructure – status report 2007*[3], Annex 1.. ex=existing, pl=planned.

From the table we can conclude that noise mitigation has become more prominent since 2005/2006 and certainly will be even more prominent in the decade to come. Noise barriers and façade insulation are still the major alternatives. Track absorbers become more important in a few countries only.

6 CC ANALYSIS EU COUNTRIES

6.1 Barriers, track absorbers and window insulation

Following the alternative approach for filling out missing data (see §5.3) the LCC analysis for existing and planned measures is given in Table 7 and Table 8. These figures are the aggregated results from the questionnaire. Net Present Value (NPV) and Equivalent Annual Costs (EAC) values are given in million Euro, at a discount rate of 3%.

LCC ANALYSIS EU / EXISTING MEASURES [million €]											
			track measures			noise barriers			window insulation		
code	country	price index	km	NPV	EAC	km	NPV	EAC	houses	NPV	EAC
BE	Belgium	1.08	0.0	0.0	0.0	120	259.7	9.4	4000	64.7	1.9
CZ	Czech Republic	0.70	0.0	0.0	0.0	115	162.0	5.9	1500	15.7	0.5
DE	Germany	1.01	140.0	74.9	4.3	1050	2185.6	79.0	46000	128.0	3.9
DK	Denmark	1.37	0.0	0.0	0.0	70	190.8	6.9	10000	205.3	6.2
ES	Spain	0.93	0.0	0.0	0.0	150	171.3	6.2	3000	41.9	1.3
FR	France	1.08	50.0	28.5	1.6	300	649.3	23.5	10000	161.7	4.9
FI	Finland	1.21	0.0	0.0	0.0	60	145.6	5.3	4000	72.8	2.2
HU	Hungary	0.68	0.0	0.0	0.0	50	68.5	2.5	1500	15.3	0.5
IT	Italy	1.02	20.0	10.8	0.6	50	102.6	3.7	8000	122.3	3.7
NL	Netherlands	1.00	99.1	52.5	3.0	420	805.5	29.1	14347	79.4	2.4
UK	United Kingdom	0.96	0.0	0.0	0.0	5	9.0	0.3	0	0.0	0.0
CH	Switzerland	1.26	0.0	0.0	0.0	348	822.4	29.7	24389	164.9	5.0
NO	Norway	1.35	0.5	0.4	0.0	50	150.2	7.7	100	2.6	0.1
AU	Austria	1.02	20.0	10.8	0.6	450	923.5	33.4	2000	30.583	0.92

Table 7. Amount and LCC analysis for existing measures in million €, at a discount rate of 3%.

From the table it can be seen, that Germany has faced the largest NPV by far. Germany alone accounts for approx. 30% of the total Net Present value of noise barriers as well as window insulation.

LCC ANALYSIS EU / PLANNED MEASURES [million €]											
			track measures			noise barriers			window insulation		
code	country	price index	km	NPV	EAC	km	NPV	EAC	houses	NPV	EAC
BE	Belgium	1.08	0	0.0	0.0	30	64.9	2.3	2000	32.3	1.0
CZ	Czech Republic	0.70	0	0.0	0.0	15	21.1	0.8	1500	15.7	0.5
DE	Germany	1.01	0	0.0	0.0	300	936.7	33.8	10000	151.5	4.6
DK	Denmark	1.37	10	7.3	0.4	20	27.3	1.0	6500	133.5	4.0
ES	Spain	0.93	10	4.9	0.3	130	297.0	10.7	2000	28.0	0.8
FR	France	1.08	50	28.5	1.6	30	64.9	2.3	5000	80.8	2.4
FI	Finland	1.21	0	0.0	0.0	10	24.3	0.9	3000	54.6	1.6
HU	Hungary	0.68	0	0.0	0.0	10	13.7	0.5	1000	10.2	0.3
IT	Italy	1.02	50	27.0	1.6	500	1539.2	55.6	8000	122.3	3.7
NL	Netherlands	1.00	450	238.3	13.7	1100	2428.7	87.8	10000	150.0	4.5
UK	United Kingdom	0.96	28	14.3	0.8	33	59.6	2.2	500	2.8	0.1
CH	Switzerland	1.26	20	13.4	0.8	113	384.7	13.9	61300	414.4	12.5
NO	Norway	1.35	0	0.0	0.0	10	30.0	1.5	200	5.1	0.2
AU	Austria	1.02	0.0	0.0	0.0	50	102.7	3.71	1000	15.3	0.46

Table 8. Amount and LCC analysis for planned measures in million €, at a discount rate of 3%.

LCC ANALYSIS EU / EXISTING MEASURES +PLANNED MEASURES [million €]											
			track measures			noise barriers			window insulation		
code	country	price index	km	NPV	EAC	km	NPV	EAC	houses	NPV	EAC
BE	Belgium	1.08	0.0	0.0	0.0	150	324.7	11.7	6000	97.0	2.9
CZ	Czech Republic	0.70	0.0	0.0	0.0	130	183.1	6.6	3000	31.5	0.9
DE	Germany	1.01	140.0	74.9	4.3	1350	3122.3	112.8	56000	279.5	8.4
DK	Denmark	1.37	10.0	7.3	0.4	90	218.0	7.9	16500	338.8	10.2
ES	Spain	0.93	10.0	4.9	0.3	280	468.3	16.9	5000	69.9	2.1
FR	France	1.08	100.0	57.1	3.3	330	714.3	25.8	15000	242.5	7.3
FI	Finland	1.21	0.0	0.0	0.0	70	169.8	6.1	7000	127.4	3.8
HU	Hungary	0.68	0.0	0.0	0.0	60	82.2	3.0	2500	25.5	0.8
IT	Italy	1.02	70.0	37.8	2.2	550	1641.8	59.3	16000	244.7	7.4
NL	Netherlands	1.00	549.1	290.8	16.7	1520	3234.2	116.9	24347	229.4	6.9
UK	United Kingdom	0.96	28.0	14.3	0.8	38	68.7	2.5	500	2.8	0.1
CH	Switzerland	1.26	20.0	13.4	0.8	461	1207.1	43.6	85689	579.3	17.4
NO	Norway	1.35	0.5	0.4	0.0	60	180.2	9.2	300	7.7	0.3
AU	Austria	1.02	20.0	10.8	0.6	500	1026.2	37.1	3000	45.9	1.4

Table 9. Amount and LCC analysis for existing + planned measures in million €, at a discount rate of 3%.

LCC ANALYSIS EU / TOTAL /EXISTING+PLANNED [million €]	track measures			noise barriers			insulation		
	km	NPV	EAC	km	NPV	EAC	houses	NPV	EAC
EU-14	948	512	29	5589	12641	459	240836	2322	70

Table 10. Amount and LCC analysis for existing + planned measures in million €, at a discount rate of 3% for the 14 countries in this research.

Annex 6 presents the total NPV and EAC for existing and planned measures in table and graphical representation.

Figure 6-a Total NPV/km^2, per country, rolling stock measures excluded:

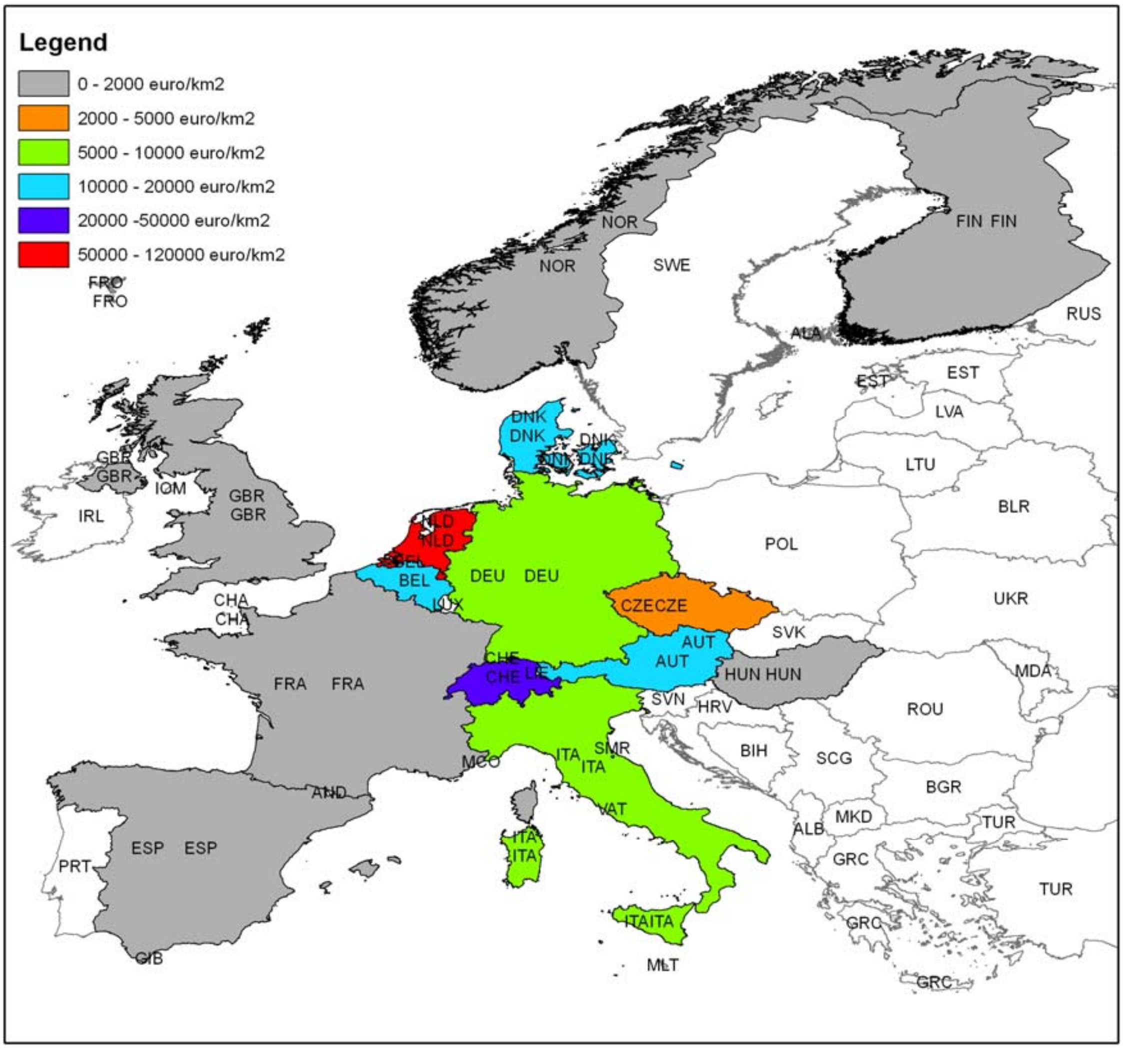

Figure 6-a. NPV per km^2 for noise barriers, track absorbers and window insulation

Switzerland and the Netherlands have the most restrictive noise legislation. Therefore, the Netherlands and Switzerland have the highest density of measures per km^2 and the highest NPV/km^2.

The same conclusion can be drawn from Figure 6-b, the EAC (equivalent annual cost) per country and per measure type. In most of the countries the EAC for barriers is the highest EAC, followed by window insulation. In Finland and Denmark the EAC for window insulation is higher than the EAC for barriers, because there are relatively few existing and planned noise barriers, but significant amounts of houses with window insulation.

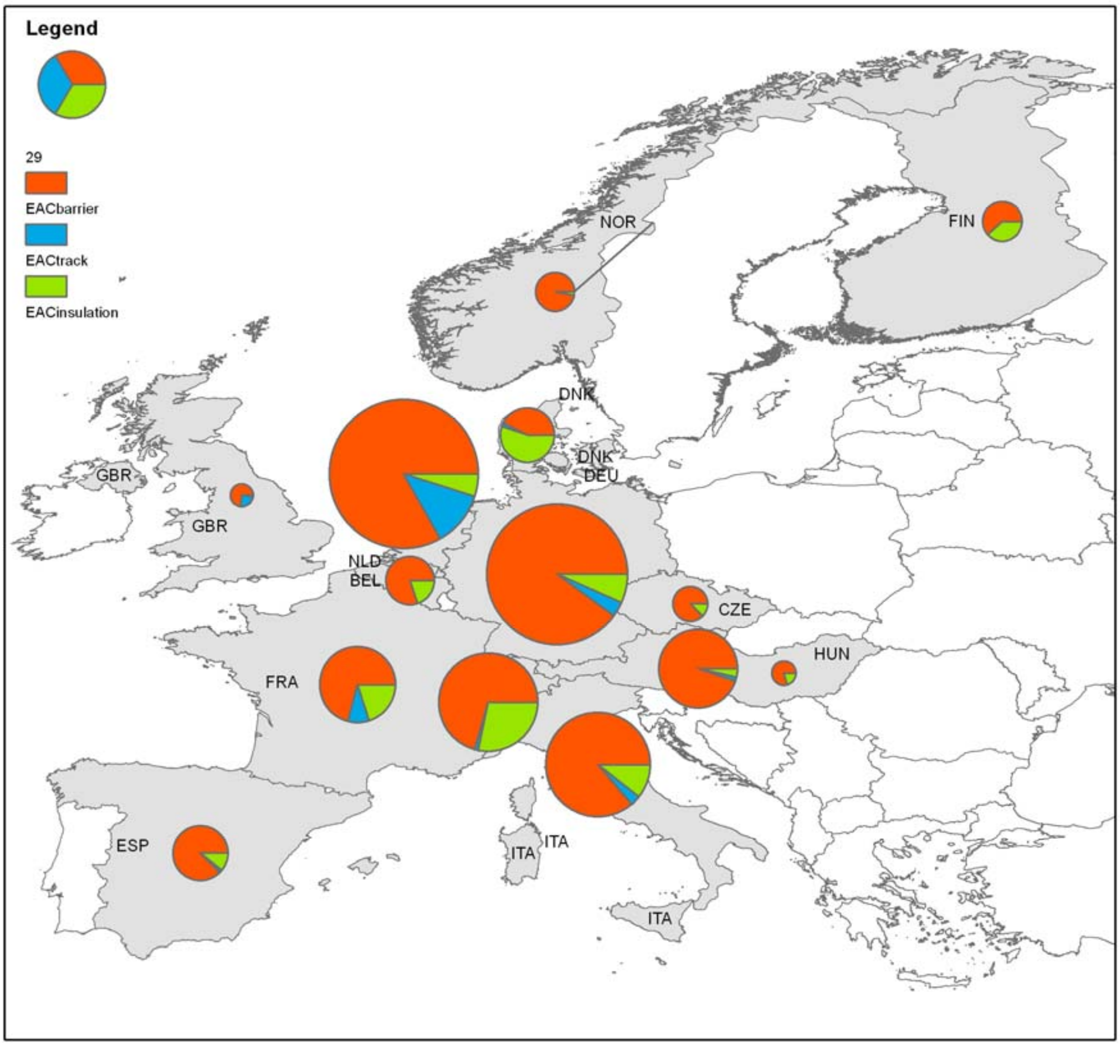

Figure 6-b. Total EAC per country and EAC per measure type.

6.2 Sensitivity analysis

To test the sensitivity of the results of the LCC analysis for the total amount of existing and planned measures (Table 10), several parameters were varied in the final analysis.

	track measures			noise barriers			insulation			Sensitivity Average [%]	
	km	NPV	EAC	km	NPV	EAC	houses	NPV	EAC	NPV	EAC
Default	948	512	29	5589	12641	459	240836	2322	70		
Discount rate 3% → 5%	948	499	35	5589	11095	588	240836	2304	115	-5%	38%
Discount rate 3% → 2%	948	520	27	5589	13891	403	240836	2344	48	4%	-17%
Window insulation Initial cost only	948	512	29	5589	12641	459	240836	2288	69	-0.5%	-0.5%
All measures +25%	1185	639	37	6986	15801	574	301045	2902	87	25%	25%
All measures -25%	711	384	22	4191	9481	345	180627	1741	52	-25%	-25%

Table 11. Sensitivity analysis for existing + planned measures in million €.

The following conclusions can be drawn from this sensitivity analysis:

- The EAC is more sensitive than the NPV for variations in the discount rate.
- The effect of renewal of façade insulation in the total LCC is less than 1%.
- NPV and EAC are linear with variations in length and amount of measures.

6.3 Rolling stock retrofitting

§4.3.3 presents investment costs and yearly costs for K-blocks, LL-blocks and wheel dampers as a result from the study *Whispering Train* in the Netherlands. Based on 350.000 wagons in Europe, the NPV and EAC are:

type	Investment cost (average)	Maintenance cost/year	Lifecycle [year]	NPV [Million €]	EAC [Million €]	NPV/ Wagon [€]	EAC/ wagon [€]
LL-block	2.100 €	400 €	40	4000	173	11346	491
K-blocks	8.000 €	300 €	40	5200	226	14934	646
Wheel absorbers	27.000 €	400 €	20	11500	775	32951	2215

Table 12. NPV and EAC for 350.000 freight wagons in Europe

The investment costs of LL-blocks are approx. 25% of the investment costs of K-blocks. NPV and EAC for LL-blocks are approx. 75% of NPV for K-blocks, making the difference in LCC less distinctive.

6.4 Retrofitting scenarios

This chapter gives an estimation of the overall replacement costs (extrapolated value) for composite brake block in time, taking into account different scenarios in noise policies such as international regulations (e.g. TSI) and EU recommendations (e.g. future NDTAC, emission ceilings or ban of cast iron blocks).

Six scenarios were included:

	Scenario name	description	End year	Wagons/year Retrofit *
1	**all in 2012**	Retrofit all freight wagons in 2012[2]	2012	330.000
2	**Forced retrofitting**	Forced retrofitting in 2016[3]	2016	74.250 + 8.250
3	**1 cycle**	Retrofit all freight wagons in one maintenance cycle of 7 years	2019	38.893 + 8.250
4	**2 cycles**	Retrofit all freight wagons in two maintenance cycles of 7 years	2026	15.322 + 8.250
5	**3 cycles**	Retrofit all freight wagons in three maintenance cycles of 7 years	2033	7.465 + 8.250
6	**do nothing**	Do nothing: replacement of CI blocks through fleet renewal only	2052	8.250

Table 13. last column: number of wagons to be annually retrofitted in the specific scenario, including fleet renewal

In this analysis the following starting points were used:

- The reference year is 2012. NPV is calculated to this reference year.

[2] Obviously, this is not practically achievable. This scenario is taken into account for comparison reasons only

[3] Similar to option 1, this is not a realistic option, but as an extreme it is interesting to assess the cost of this option

- This NPV can be considered as an estimation of overall replacement cost in the scenario under concern
- In 2012, 20.000 freight wagons have been retrofitted or replaced, 330.000 wagons are not yet retrofitted
- The fleet renewal is considered to be 2.5%/year which is 8250 wagons/year. In 2052 all wagons have been replaced if no special scenario is applied.
- Retrofitting scenario 2- 5 are a combination of autonomous renewal of 2.5%/year and the retrofitting scenario
- Autonomous renewal is considered to be zero costs, because cast iron blocks should be replaced anyway according to TSI
- Discount rate is 3%
- Each retrofitting programme is considered to be linear in time between 2012 and the end year of the programme.

Table 14 and Figure 6-c present the total NPV in the reference year 2012 per scenario and the number of wagons to be treated or replaced

	retrofitting NPV [billion €]					
	all in 2012	ban in 2016	1 cycle	2 cycles	3 cycles	do nothing
LL blocks	3.97	3.13	2.75	1.96	1.31	0
K blocks	5.23	4.12	3.62	2.58	1.72	0

Table 14. NPV in billion € for 6 scenario's for K-block and LL-Blocks, at a discount rate of 3%, reference year 2012.

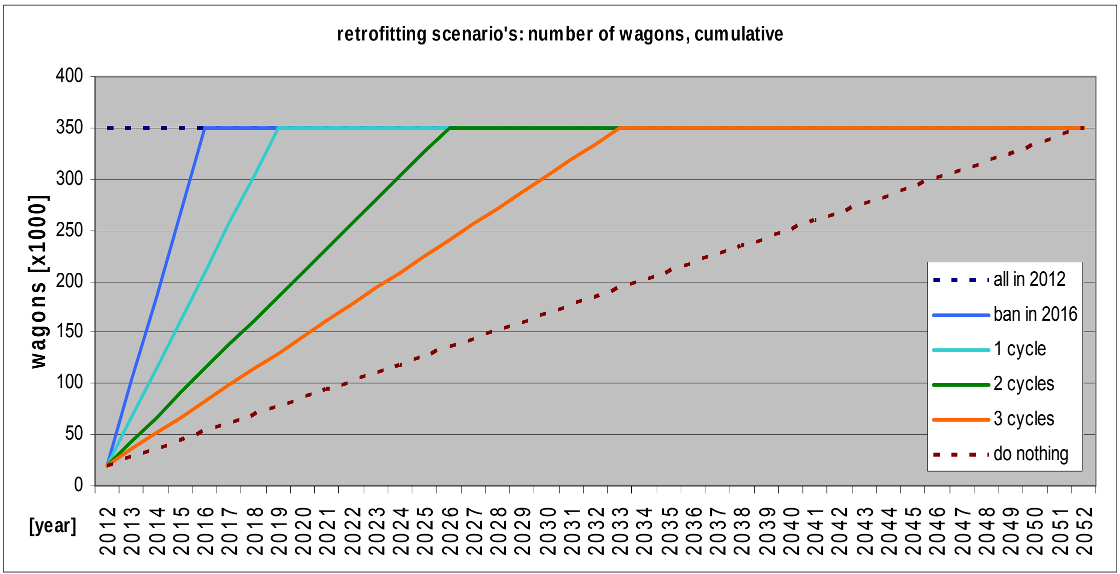

Figure 6-c. Duration of various retrofitting scenarios

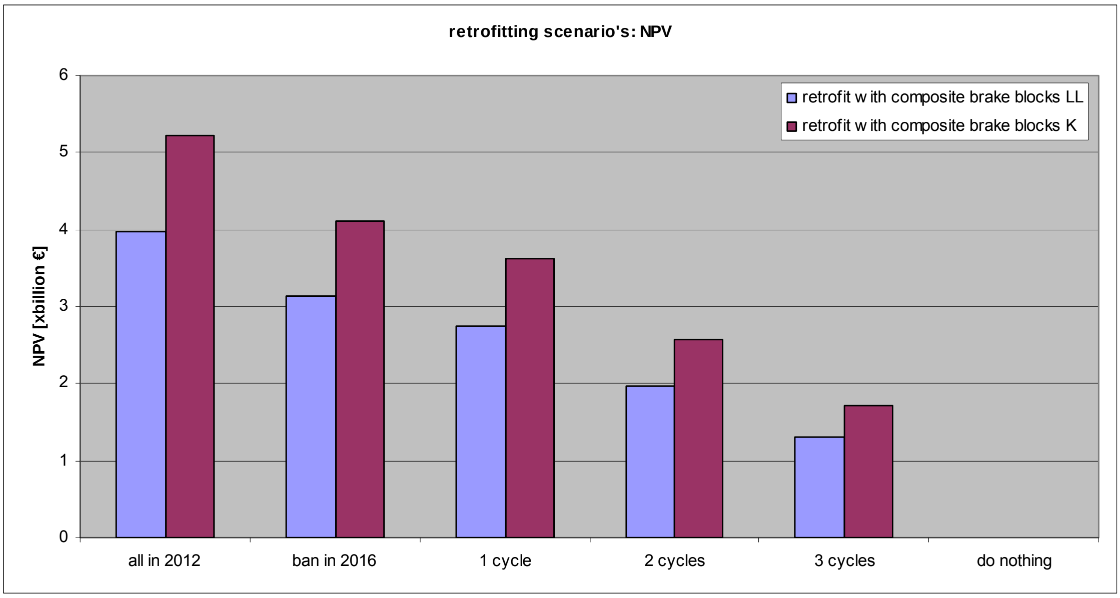

Figure 6-d. NPV in billion € for 6 scenarios for K-blocks and LL-blocks, at a discount rate of 3%, reference year 2012.

Conclusion:

The longer the programme, the lower the total NPV for the programme. If no extra programme is applied (scenario "do nothing", only fleet renewal) the NPV is zero (because cast iron blocks should be replaced anyway).

If all freight wagons are retrofitted in the reference year (2012), the replacement cost equals the total NPV value calculated in section 6.2 .

7 COST BENEFIT IN STAIRRS

This survey provides an update of the cost and benefit figure from the STAIRRS project. The basis for this revision is the original spread sheet produced in the STAIRRS project using the latest information from this project. §7.1 resumes the assumptions made in the STAIRRS project § 7.2 resumes the theoretical background of the STIARRS cost-benefit analysis.

The STAIRRS cost-benefit figure was based on a thorough analysis of the main lines in Europe (Eurano software), including a GIS of the urban areas along these lines. Rough assumptions were made about the national legislation (60 dB was considered a general target level in all EU countries), and the cost of noise mitigation was based on investment -, yearly - and lifecycle costs. Some of these elements need improvement, using today's know-how.

7.1 STAIRRS – Cost-benefit assumptions

Discount rate
The rate of cost discounting was assumed to be uniform for all countries modeled in STAIRRS. A rate of 5% has been chosen, which is based on current practice throughout Europe.

Lifecycle costs measures
Average Lifecycle costs for measures in STAIRRS can be found in *STAIRRS FINAL TECHNICAL REPORT*[4] , table 4 and 5. The basic parameters as well as minimal and maximum costs were based on information obtained from the participating railway as well as information supplied by the UIC Sub commission Noise and Vibration as well as the EU Working Group Railway Noise.

Table 15. average lifecycle costs from STAIRRS report [4, table 4 and 5]
Notes: * no maintenance costs for insulated windows were considered
** Acoustical Grinding is modeled as maintenance costs.

		Noise barriers			*Insulated windows*	*Rolling stock improvement (freight cars)*			*Rolling stock improvement (passengers cars)*			*Track improvement*	
		2m	*3m*	*4m*	per house	Brakes 1	Brakes 2	Optimized	Brake 1	Brake 2	Optimized	Tuned	Grinding**
	units				*4 windows**	Freight - 10dB	Brakes : k-blocks	wheels			wheels	Absorbers	
Measure No		1	2	3	4	5	6	7	8	9	10	11	12
Investment cost per unit, I	€	933	1,215	1,475	5,600	9,881	4,996	11,557	0.00	0.00	0.00	500	0
Lifetime per measure, T_L	Years	25	25	25	80	40	40	10	40	40	10	30	80
Start of maintenance, t_M	Years	1	1	1	1	1	1	1	1	1	1	1	1
Frequency of maintenance, t_{Mp}	Years	1	1	1	1	1	1	1	1	1	1	1	5
Maintenance costs, M	€	18.66	24.30	29.50	0.00	0.00	0.00	231.16	0.00	0.00	0.00	10.00	10.32
Maintenance part	%	2%	2%	2%	0%	0%	0%	2%	0%	0%	2%	2%	
Removal costs, R	€	93.30	121.50	147.50	0.00	494.05	249.81	0.00	0.00	0.00	0.00	50.00	0.00
Removal part	%	10%	10%	10%	0%	5%	5%	0%	5%	5%	0%	10%	0%
p-rate		2.39	2.39	2.39	48.56	6.04	6.04	0.63	6.04	6.04	0.63	3.32	48.56

Short-term approach

Different noise control strategies (for example consisting of varying combinations of noise control measures) were compared based on investment costs. These measures have a benefit during their lifetime only. This approach implies that technological advances will progress during the lifetime of the products thus requiring an analysis and a new decision at the end of their lifetimes. This approach therefore does not include costs to replace measures.

Long-term approach

The reason for the development of the long-term approach in STAIRRS was that the costs and benefits had to be accounted for over a long period. The general environmental impacts of the railways and the specific noise impacts do not stop after the lifetime of a measure. The second reason is to come up with an evaluation which accounts for the different lifetimes of the measures. For example, a noise barrier with a lifetime of 25 years cannot be compared to a rolling stock measure with a lifetime of 40 years. Considering two noise barriers lifetimes would not be adequate either, when the end of the modeled period is 40 years because of the lifetime of a rolling stock measure. The solution to the problem of finding an appropriate time frame could be to choose the lowest common multiple (LCM) of the lifetimes of all the measures. This would be 4200 years considering the lifetimes of 25, 30, 35, and 40 years.
The long-term approach assumes that at the end of the lifetime of a measure, it is not only removed (as in the short term approach), but also replaced, so that the benefits are continuous.

Extrapolation

An extrapolation methodology was developed to determine optimum noise control strategies for any geographic area of interest, be it Europe as a whole, the E.U. or an individual country. Noise calculations and determination of the extent of required measures were undertaken on this representative data base and were subsequently extrapolated by the ratio between line lengths in the area of interest and in the representative data base. Cost-effectiveness calculations are done on the extrapolated data.

Definition of benefit, effectiveness and efficiency

In STAIRRS, these terms are defined as follows:

- *Benefit*: Improvement in noise situation for line side residents expressed in monetary terms.
- *Effectiveness:* Physical, non-monetary “benefits” of a measure.
- *Efficiency:* Ratio of costs and effectiveness.

The major elements of the STAIRRS cost-effectiveness analyses are given below:

The cost function:

For the short term approach, the cost function is the sum of all investment, maintenance and removal costs for a programme, until the end of the modeling period. The investment costs are summed for each measure implemented during the 10-year investment programme. The maintenance costs are added for each measure and each year from the start of maintenance to the end of the lifetime of the measure. Removal costs occur at the end of the lifetime for those measures that must be removed (e.g. noise barriers). All costs are discounted to the first year of the programme. The cost function is described in detail in annex 3 of *STAIRRS, Deliverable 10 - Synthesis Report Work Package*[7].

$$PC_x = \sum_{i=1}^{10} \frac{\sum_{j=1}^{n} I_{ji}}{(1+r)^{i-1}} + \sum_{i=1}^{10} \sum_{j=1}^{n} \frac{\sum_{k=i+S_j-1}^{i+a_j-1} m_{ijk}}{(1+r)^k}$$

where:

$PC_x =$ present costs for programme X (in €).
i = the year of investment ; 1<*i*<10. Year 1 may be 2005 for instance.
j = measures (noise barriers, improvement of the rolling stock, brakes, etc.). 1<*j*<*n*, where *n* is the number of different measures considered in the programme X. This number can be lower than the number of measures considered within STAIRRS. (see Specification Document).
$I_{ij} =$ investment costs for measure *j* in year *i*.
r = discount/interest rate, at present assumed to be uniform for all countries modeled in STAIRRS.
$s_j =$ period after which maintenance is needed for the first time (following the investment) for the measure *j*.
$a_j =$ lifetime of measure *j*.
$m_{ijk} =$ maintenance and repair costs for measure *j* in year *k*, for the investments made in year *i*. These costs might not occur in each year within this period.

The formula for PC_x is of the same form as the NPV function (see formula 1). Therefore , PC_x in STAIRRS is an NPV term.

The effectiveness function:
The present benefit function (PB) expresses the effectiveness as the reduction of annoyed persons or of persons with noise reception values above an L_{den} of 60 dB(A) multiplied by the number of years during which this reduction lasts (persons no longer above an L_{den} of 60 dB(A) * years). This unit gives a total effectiveness for a definite number of years. STAIRRS (Eurano) calculations could not be done to determine cumulated benefits in every year, therefore the effectiveness was interpolated. Two different indicators were used to describe the effectiveness:

- Reduction in the number of persons above an L_{den} of 60 dB (A).
- Reduction of the number of annoyed people (compare chapter 2.2 noise calculation)

The benefit function is described in detail in annex 3 of *STAIRRS, Deliverable 10 - Synthesis Report Work Package*[7].

7.2 The STAIRRS Cost-benefit figure

The widely known STAIRRS cost-benefit figure, showing the extrapolated data to Europe not including costs for insulated windows and using the expected number of wagons to be improved based on information from the UIC action programme noise reduction freight traffic (November 2001) for the 21 countries considered, can be found in the report *STAIRRS, Deliverable 10 - Synthesis Report Work Package*[7].

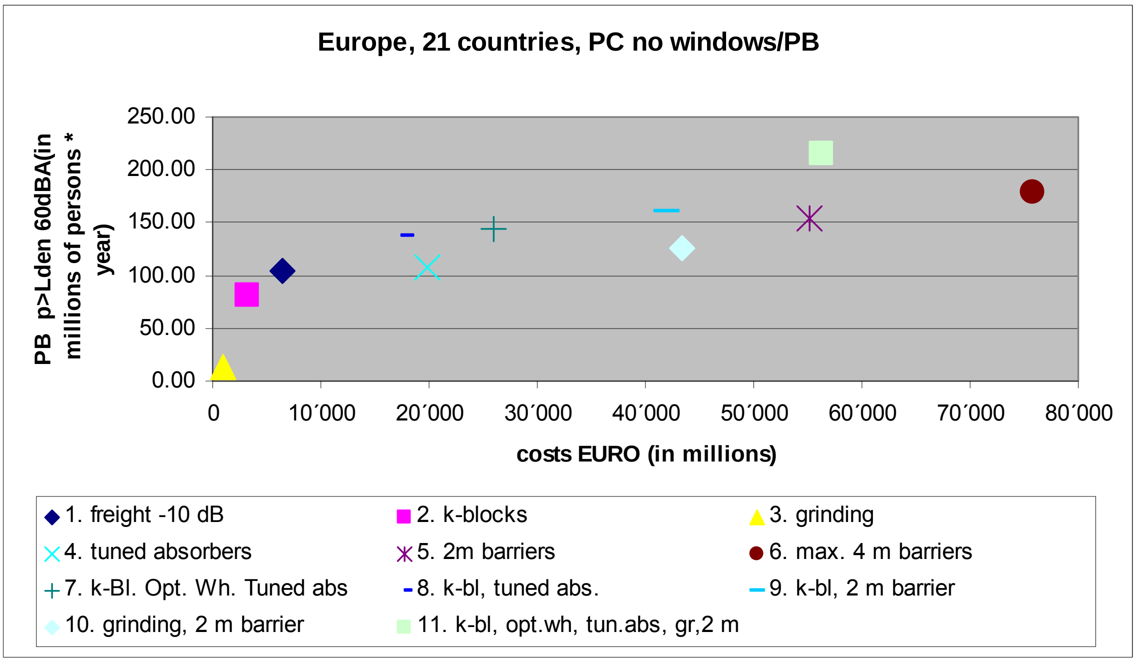

Figure 7-a. *Cost-benefit figure from report STAIRRS, Deliverable 10 - Synthesis Report* Work Package, Figure 3.2.2b [7]: Short term cost-effectiveness of programs not including windows. Number of wagons from UIC action programme noise reduction freight traffic. PC: present costs, PB: present benefits or effectiveness, PB L_{den} p>60 dB (A): effectiveness as reduction of number of persons above Lden of 60 dB(A), k-Bl: composite brake blocks, Opt. Wh.: optimized wheels, tun. abs.: tuned rail absorbers, gr: grinding, 2 m: 2 m noise barriers.

The total number of wagons was based on UIC statistics (726.882 wagons).

7.3 The updated STAIRRS Cost-benefit figure

In §7.1 it is shown that the formula for PC_x is an NPV function. In STAIRRS, noise data was collected for a total length of 10,974 km, representing about 10 % of the total line length in the seven countries considered. With extrapolation to 21 countries, 10 noise control programs were studied.

Figure 7-b. Map showing lines chosen for acoustical data collection in STAIRRS.

Acoustic recalculation of the STAIRRS programs is not within the scope of this project. Therefore, the only part in the STAIRRS dataset that can be updated with the NPV and EAC results from this study, is to substitute the STAIRRS PC_x with the NPV from this study, and leaving the amount of measures from the STAIRRS study unchanged.

For barriers and track measures the relation will be:

$$NPV_i = NPV_i\, per\_unit\_length \times Length_i \qquad (4)$$

Where the NPV_i for measure i per unit length comes from this study, and the Length is taken from the STAIRRS study.

Measure	NPV at discount rate 3%	NPV at discount rate 5%	Unit
freight -10 dBA	14934	13148	€/wagon
k-blocks	14934	13148	€/wagon
Opt Wheels	32951	31985	€/wagon
Tuned Abs	540	526	€/m

Grinding	0	0	€/m
NB 2m	1810	1588	€/m
NB 3m	2714	2382	€/m
NB 4m	3619	3177	€/m
houses w. wind	9640	9568	€/house

Table 16. NPV per unit measure at a discount rate of 3% and 5%

Substituting the STAIRRS PC_x with this NPV calculation results in:

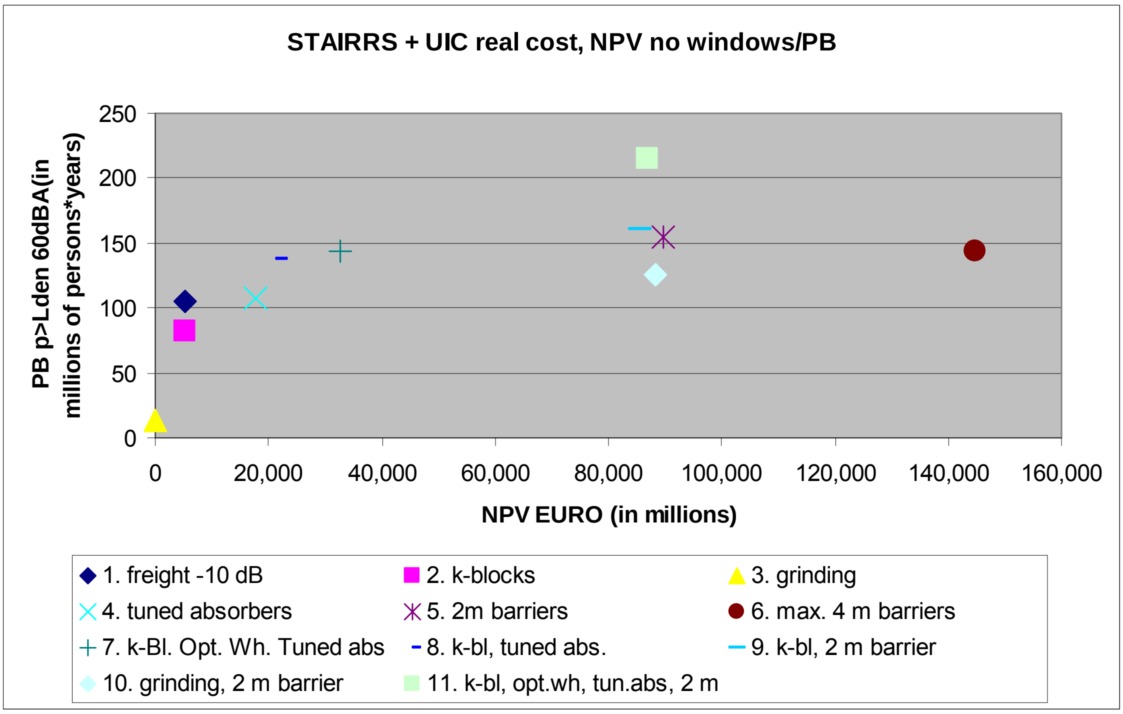

Figure 7-c. STAIRSS cost-benefit graph with NPV instead of PCx, with 350.000 wagons, discount rate 3%.

Comparing the updated STAIRRS cost-benefit figure with the original one (Figure 7-a) the following general observations can be made:

1. NPV cost are generally higher than STAIRRS present costs PCx
2. the shape of the graph is roughly the same, programs are placed on slightly different relative positions compared to each other
3. The position of the programs with retrofitting measures shift relatively to the left compared to the STAIRRS figure. The reason for this is approx. halving of the amount of wagons in the present situation
4. A change in discount rate from 3% to 5% gives a change in NPV of -2% - -12%, depending on the programme.
5. A change of ± 10% in the number of wagons gives a change in NPV costs of ± 0-10% in NPV depending on the programme.

Both the original and the updated figure are given in Annex 8 for comparison.

The STAIRRS programs with retro-fitting (1, 2, 7, 8, 9 and 11) shift to the left. This means the same benefit can be reached with retrofitting less freight wagons. (350.000 instead of 710.000). This reconfirms and strengthens the conclusion that retro fitting is the best option.

As can be seen from §6.3, the NPV and EAC of LL-blocks is approx. 25% lower than the values for K-blocks. If we substitute the LL-block NPV in STAIRRS programme 2 (K-blocks), the total NPV will be 25% lower for the figure without window insulation, and 4% lower for the figure with window insulation.
Assuming that the acoustic reduction of K-blocks and LL-block is comparable (on standard EU-track with average roughness), this reconfirms that LL-blocks are more cost effective than K-blocks, and that retro fitting is the best option.

8 CONCLUSIONS

The overall aim of the study is to support the infrastructure manager's awareness of maintenance and replacement costs of existing noise mitigation measures.
The project has gathered 20 years of real experience with maintenance cost on the most frequently used noise measures (noise barriers, insulation of buildings, track absorbers and acoustic rail grinding), to analyze the replacement costs of noise mitigation measures in terms of Net Present Cost (NPV) and Equivalent Annual Costs (EAC).

In this project the following methodology was used:

1. Parallel development of a lifecycle Cost (LCC) model and a questionnaire.
2. Distribution and collection of the Questionnaire including follow-up for better response
3. In case of missing data application of alternative approach
4. LCC analysis per country and for all countries together for existing and planned measures
5. conversion of LCC cost to NPV/unit measure
6. Update stairs figure with NPV/unit measure

The questionnaire was distributed to the contact points by sending out by e-mail in January 2012. The questionnaire contained an Excel form and a letter (see Annex 2) with explanation of the Questionnaire and the aim of the project. An e-mail alert was sent in February 2012 and after this, every contact point was offered personal assistance with filling out the questionnaire. A second round of consultation was held in April 2012.

In addition to the questionnaire, END action plans were studied. The END action plans are generally too global to be used in this research.

The conclusions that can be drawn from the response on the questionnaire are:

- Collection of LC Costs is complicated. The LCC research available in the Netherlands is not evident for other countries and is/might be difficult to obtain
- Estimation of existing and planned measures is not easy either, where estimation of planned measures is more difficult than existing measures

An alternative approach is used to fill out the data not provided in the Questionnaire.

The result of the LCC analysis per country can be expressed in a NPV/km^2. Switzerland and the Netherlands have the most restrictive noise policies. Therefore, the Netherlands and Switzerland have the highest density of measures per km^2 and the highest NPV/km^2.

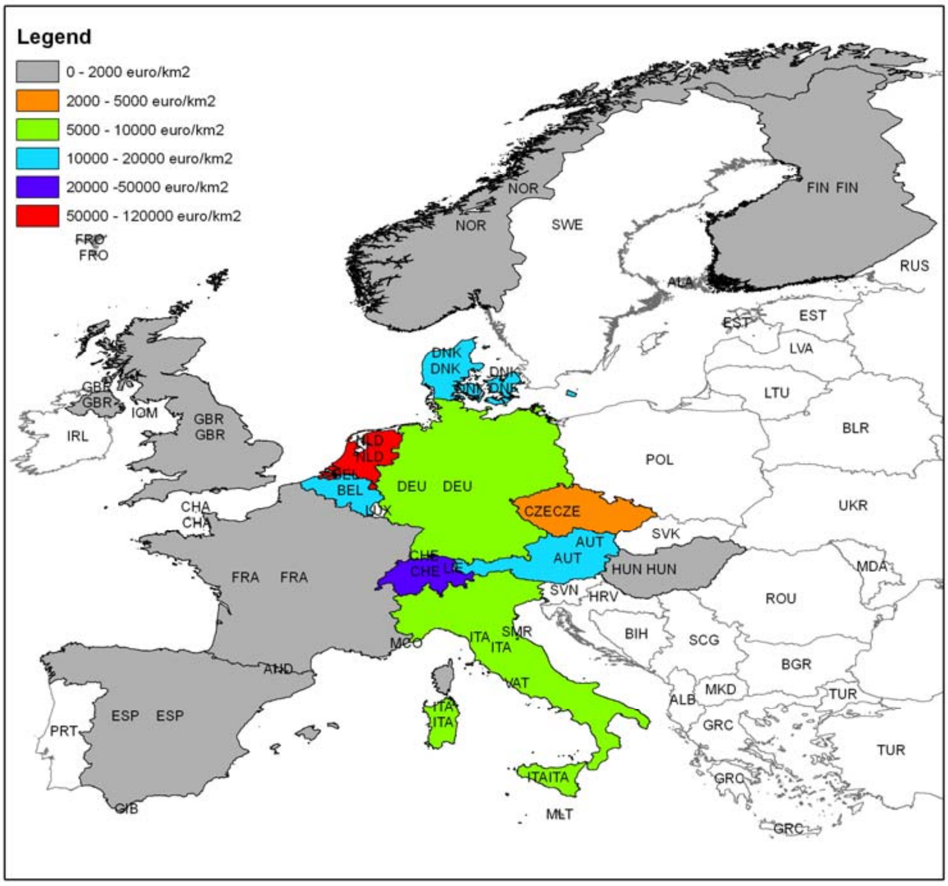

Figure 8-a. NPV per km2 for noise barriers, track absorbers and window insulation, rolling stock measures excluded

Acoustic recalculation of the STAIRRS programs is not within the scope of this project. Therefore, the only part in the STAIRRS dataset that can be updated with the NPV and EAC results from this study, is substitute the STAIRRS PC_x with the NPV from this study, and leaving the amount of measures from the STAIRRS study unchanged.

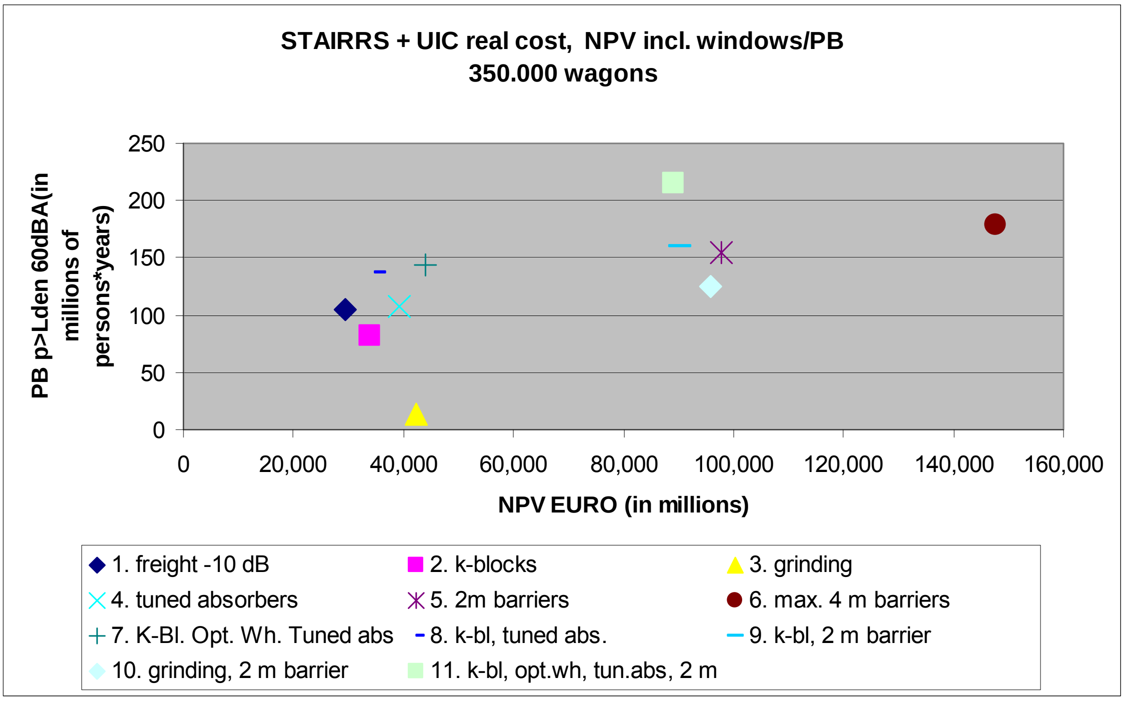

Figure 8-b. updated STAIRRS cost-benefit figure with NPV instead of PCx, with 350.000 wagons, discount rate 3%.

The STAIRRS programs with retro-fitting (1, 2, 7, 8, 9 and 11) shift to the left. This means the same benefit can be reached with retrofitting less freight wagons. (350.000 instead of 710.000). This reconfirms retro fitting as the best option.

As can be seen from §6.3, the NPV and EAC of LL-blocks is approx. 25% lower than the values for K-blocks. If we substitute the LL-block NPV in STAIRRS programme 2 (K-blocks), the total NPV will be 25% lower for the figure without window insulation, and 4% lower for the figure with window insulation.
Assuming that the acoustic reduction of K-blocks and LL-block is comparable, this reconfirms that LL-blocks are more cost effective than K-blocks, and that retro fitting as the best option.

To test the sensitivity of the results of the LCC analysis for the total Amount of existing and planned measures several parameters were varied in the final analysis. The following conclusions can be drawn from this sensitivity analysis:

- The EAC is more sensitive than the NPV for variations in the discount rate.
- The effect of renewal of façade insulation in the total LCC is less than 1%.
- NPV and EAC are linear with variations in length and amount of measures.

The accuracy of the estimation of the length and amount of track and propagation measures in the questionnaires is assumed to be ±20%, which results in an accuracy of the NPV and EAC values of ±20%.

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Links

(a) network length: http://www.atheglobal.co.uk/advanced-international-diploma-in-travel-a-tourism/15-unit-3-world-transport/119-european-railway-network

(b) network length: http://www.wikipedia.org/

(c) Centre for Economic and Social Studies for the Environment , STAIRRS: http://www.ulb.ac.be/ceese/ACTIVITY/english/stairrs.htm

10 COLOFON

Client	:	Union Internationale des Chemins de Fer
Project	:	The real cost of railway noise mitigation
File	:	BA7041-101-100
Nr of pages	:	57 pages
Author	:	Paul van der Stap, Paul de Vos
Co-author	:	Paul de Vos
Checked by	:	Paul de Vos
Project leader	:	Paul van der Stap
Project manager	:	Paul de Vos
Date	:	30 January 2013

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Annex 1 The art of economics

A. Mathematical model for (long term) LCC

Discounting is a widely used technique for comparing costs and revenues occurring at different points in time on a common basis, normally the present time. It is based on the principle that a sum of money to hand at the present time has a higher value than the same sum to hand at a future date, because of the earning power of that sum in the interim.

The generic formula for calculation of the Net Present Value (NPV) by discounting is shown in equation (1):

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} = \sum_{t=1}^{T} C_t (1+r)^{-t} \qquad (5)$$

where

NPV = Net present value
C_t = Cost of item t
r = discount rate
T = analysis period in years.

The total NPV for a measure includes operation costs, maintenance costs, replacement costs, and residual values / disposal costs:

$$NPV = I + A + C + D - S \qquad (6)$$

where

I = initial or investment cost
A = the present value of annually recurring operating, maintenance and repair cost
C = the present value of non-annually recurring operating, maintenance and repair cost
D = the present value of disposal/replacement costs
S = the present resale value

Kishk and Al-Hajj (2000) [2] developed a life cycle costing model, which is shown as equation [3]. In this model, the discount factors for annual costs and non-annual costs are formulated for simplifying the time and effort required in the computation process. Reworking formula [2] for measures gives formula [3]:

$$NPV_i = I_i + PWA \sum_{j=1}^{nari} A_{ij} + \sum C_{ik} PWN_{ik} + PWS \times \left(D_i - S_i\right) \qquad (7)$$

where

I_i= the initial cost of measure i;

PWA = present worth factor for annual recurring costs $= \frac{1}{r}\left[1-(1+r)^{-T}\right]$

A_{ij} = annual recurring costs *j* of measure *i*;
C_{ik} = non-recurring costs *k* of measure *i*.
D_i = disposal costs of measure *i*.
S_i = resale value of measure *i*.
T = total lifecycle in years

PWN = the present worth factor for a non-annual recurring cost $= \frac{1-(1+r)^{-n_{ik} f_{ik}}}{(1+r)^{f_{ik}}-1}$

PWS = the present worth factor for a single future cost over lifecycle period T = $(1+r)^{-T}$
f_{ik} = the frequencies of non-annual recurring costs C_{ik} of measure *i* in years
n_{ik} = the number of recurrences of non-annual recurring costs C_{ik} of measure I = $\frac{T}{f_{ik}}$

(if f_{ik} = 1 year or annual, PWN=PWA).

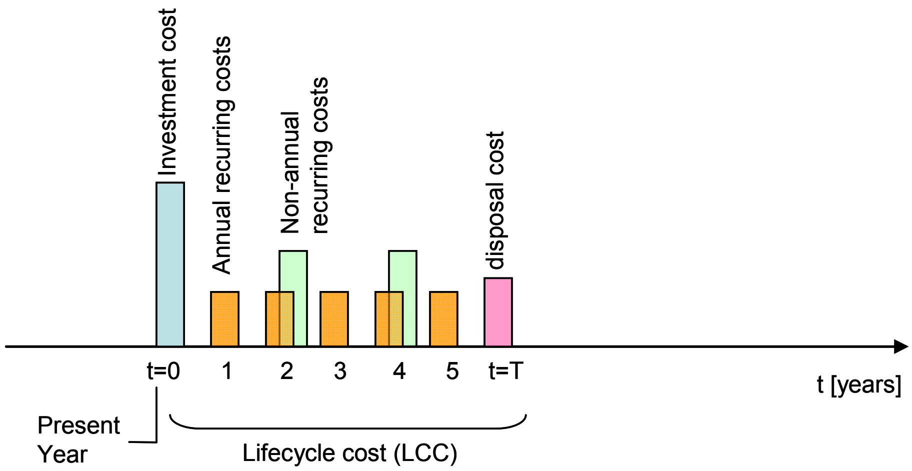

Figure 10-a. Lifecycle costs for one lifecycle

Formula (3) presents NPV of the lifecycle costs (LCC) for one lifecycle, calculated for the present year t=0. The NPV can be shifted in time by applying the present worth factor (PWS) to the lifecycle costs:

$$NPV_{t,i} = NPV_{0,i} \times (1+r)^{-t} \qquad (8)$$

where

$NPV_{0,i}$ = Net present value of measure *i* in present year t=0
$NPV_{t,i}$ = Net present value of measure *i* in present year t

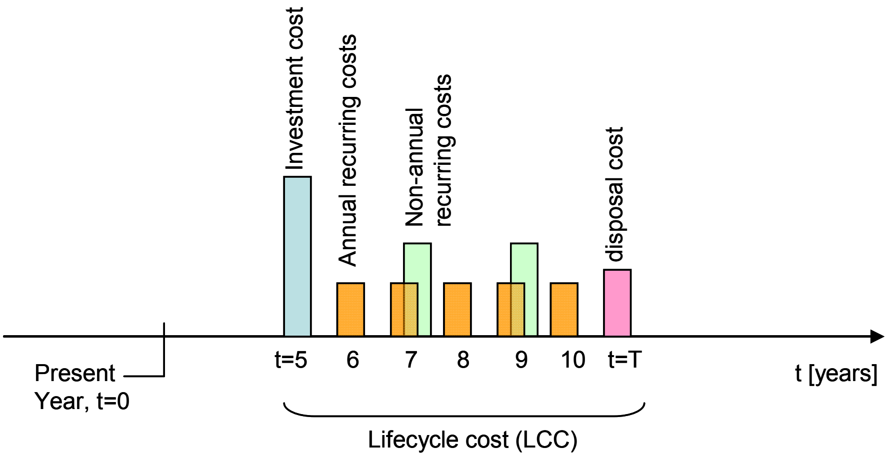

Figure 10-b. Lifecycle costs for one lifecycle shifted in time

Several lifecycles can be “linked” into a chain in time to calculate the long term lifecycle costs. With formula (4) we find:

$$NPV_{t,i} = \sum_{t=0,t_1...t}^{TP} NPV_{0,i} \times (1+r)^{-t} = NPV_{0,i} \times \sum_{t=0,t_1...t}^{TP} (1+r)^{-t} \qquad (9)$$

where
TP = total long term analysis period
$t_1 .... t_x$ = year at start of each lifecycle

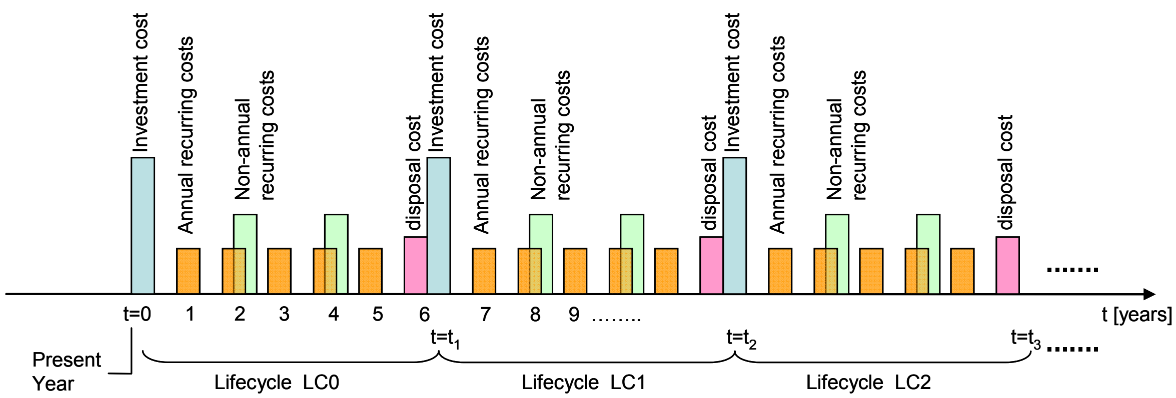

Figure 10-c. Lifecycle costs for several lifecycles in a row

If we assume the length of each lifecycle to be constant, we get:

$$t_n = t_0 + n \times LC \tag{10}$$

where

n = n[th] lifecycle
LC = length of one Lifecycle in years (frequency of lifecycle)
t_0 = year at start of lifecycle 0
t_n = year at start of lifecycle n

Substitute formula (6) into formula (5) to calculate the NPV from the total number (N) of lifecycles:

$$NPV_{n,i} = NPV_{0,i} \times \sum_{n=0}^{N} (1+r)^{-(t_0 + n \times LC)} \tag{11}$$

where

n = n[th] lifecycle

N = total number (or frequency) of lifecycles LC in total long term analysis period TP ≈ $INT\left[\frac{TP}{LC}\right]$

$NPV_{0,i}$ = Net present value of measure *i* in present year t=0 (first lifecycle)
$NPV_{n,i}$ = Net present value of measure *i* for n[th] lifecycle

By applying a present worth factor to lifecycle 0….N formula (7) can be rewritten as:

$$NPV_i = PWLC \times NPV_{0,i} \tag{12}$$

where

PWLC = the present worth factor for N lifecycles of length LC =

$$PWLC = \frac{1-(1+r)^{-N \times LC}}{(1+r)^{LC}-1} = \frac{1-(1+r)^{-TP}}{(1+r)^{LC}-1} \tag{13}$$

$NPV_{0,i}$ = Net present value of measure *i* in present year t=0, which can be obtained from formula (3).

Resume: Formula (8) represents the Net Present Value of measure *i* over a long term period TP, which contains N lifecycles of length LC years.

B. Conversion of Net Present Value (NPV) into Equivalent Annual Costs (EAC)

Rather than being expressed as a one-time net present value, a method is available to convert all costs of a measure into a uniform equivalent annual cost (EAC)[5]. The EAC of measure *i* is related to the NPV of measure i by the PWA factor as follows:

$$EAC_i = \frac{NPV_i}{PWA_i} \tag{14}$$

Where

EAC_i = Equivalent Annual Costs of measure i
NPV_i = Net present value of measure *i* in present year t=0, from formula (8)

PWA = PWA factor (present worth of annuity) for measure i = $\frac{(1+r)^{TP}-1}{r(1+r)^{TP}}$

TP = total long term analysis period

It should be noted that the EAC calculated with this method is an average number, and does not indicate the actual cost that will be incurred during each year of the life cycle.

The big advantage of using EAC is that calculation of the EAC can be simplified to one lifecycle:

$$EAC_i = \frac{NPV_i^{LC0}}{PWA_i^{T0}} \tag{15}$$

Annex 2 Letter for Questionnaire

DHV B.V.
Environmental and Sustainability
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3800 BC Amersfoort
The Netherlands
T +31 33 468 2000
F +31 33 468 2801
E info@dhv.com
www.dhv.com

Amersfoort, 16 January 2012

your ref	:	
our ref	:	MD-AF20120087
file	:	BA7040
project	:	UIC Real Cost of Noise Reduction
subject	:	
dealt with by	:	Paul de Vos
tel, e-mail	:	+31 33 4682927, paul.devos@dhv.com
classification	:	Internal use only

Dear,

The International Union of Railways UIC has contracted our company, DHV BV, to carry out a survey amongst European railway stakeholders. The objective of the survey is to assess the cost of noise reduction in a consistent way, based on common economical principles. The cost assessment shall include all cost elements, including preparation, design and planning/construction/maintenance/ renewal and disposal, for the noise mitigation measures currently applied in railway systems. In doing so, the project should come up with a better and more consistent way of comparing the cost efficiency of alternative options to mitigate noise. In particular, the project shall allow comparison of vehicle related noise mitigation options (such as retrofitting the freight fleet) against options that refer to the track (such as rail dampers), the noise propagation (such as barriers and screens) or the receiver (such as sound insulating windows).

The project's aim is to increase the infrastructure manager's awareness of maintenance and replacement costs of existing noise mitigation options and to gather 20 years of real experience with maintenance cost on the most frequently use noise measures (noise barriers, insulation of buildings, track absorbers and acoustic rail grinding), to analyze the replacement costs of noise mitigations measures and hereafter to analyze the financial risks involved.

To this effect, we herewith send you our questionnaire in digital form. We kindly request you to complete the attached questionnaire as completely as possible.

At first sight, the questionnaire may appear complex to you. Therefore we offer our assistance per telephone or email, and in addition in the following we present you with some detailed guidelines for completion of the questionnaire.

This Questionnaire in Excel format contains 5 sections (tabs):

- General

- Contact
- Existing measures
- Planned measures
- Distribution and noise limits

This questionnaire also contains an LCC section to calculate the Equal annual cost (EAC) and net present value (NPV) per measure [4].

General
Contains general information and contact details of DHV.

Contact
Your contact details.
Select your country (country code will be generated automatically).
If applicable, specify a region.

Existing measures
This section has two parts. General information about the current network and extent of existing measures.

The data to be entered in *network characteristics* should give a **rough indication** of the national network. Try to estimate the percentage of the total network length for different type of lines, and for each type the percentage of low and high traffic lines.

In the columns with heading *general* in the section *existing measures costs* please indicate if a measure is applied (yes/no). If applied, number of wagons, length, and/or number of dwellings with window insulation should be entered.

You can enter the data in the sections *noise barriers* and *window insulation* per type or for all types together if a specification per type is not possible.

The columns with heading Life Cycle Costs should contain costs per cost type for all applied measures. Please select at least one of the applicable cost types.

unit of cost: specify the unit of cost for the costs provided in the following columns.
€/wagon: cost per wagon
€ [total]: gross total costs for whole network
€/m: cost per meter noise barrier
€/m^2: cost per square meter noise barrier
€/house: window insulation cost per house

Procedural cost: All costs for a design and legal procedures
Investment cost: costs that will be incurred prior to the occupation of the measure

---

[4] Equal annual cost (EAC): the cost per year of owning and operating an asset over its entire lifespan
Net present value (NPV): the sum of the discounted future cash flows, both costs and benefits/revenues.

Annual maintenance cost: annual recurring operational, maintenance and repair cost
Non-annual maintenance cost: non-annual recurring operational, maintenance and repair cost. If specified, the period (next field) has to be filled in as well. A period of 1 year is equal to annual costs.
Period of non-annual maintenance cost: in years
Some maintenance costs are incurred annually and others less frequently. Repair costs are by definition unforeseen so it is impossible to predict when they will occur. For simplicity, all maintenance and repair costs can be treated as annual costs.
Disposal costs: costs for demolition and disposal of the measure
Resale value: or Residual value, is the net worth of a measure at the end of the lifecycle.
Lifecycle (years): The defined service life cycle of the measure, the period of time between the inception and completion of the functional need (which maybe cradle to grave)
Implementation program: give an estimation of the first year of implementation

Planned measures
This section differs on two points from the section *existing measures*.
1] Instead of the *estimation of total existing network length* the *estimation of total new planned network length (excl. existing network)* has to be filled out, together with horizon of planned tracks (future year).
2] Under *implementation program, investment program (years from start)* the number of years of the investment program has to be filled out.

Distribution and noise limit
The purpose of this section is to estimate the distribution of existing and planned measures for different reasons or environments. Also provide the national noise limit for railways.

LCC analysis
Life cycle costs (LCC) are cradle to grave costs summarized as an economics model of evaluating alternatives for equipment and projects. In this tab you can make a simple LCC analysis on NPV (Net Present Value) or EAC (Equal Annual Costs).

The first step is to select the input sheet for analysis. You can specify a discount rate; the default discount rate is 3%.
The button Analysis copies the data from the selected input sheet to this LCC sheet and calculates the NPV and EAC for ach measure.

Please feel free to contact us, either by e-mail or by telephone, in case you have any questions or need any support when filling the questionnaire.

Paul van der Stap (not on Thursdays or Fridays)	paul.vanderstap@dhv.com	+31 33 468 3128	+31 6 5201 8688
Paul de Vos	paul.devos@dhv.com	+31 33 468 2927	+31 6 2909 8228

We would appreciate to receive a first reaction by 1 February latest and we strive to have your questionnaire filled out completely by 15 February latest

Annex 3 Questionnaire

Tab general and contact information

Questionnaire for the UIC-study

Maintenance and reinvestment costs of noise reduvtion measures

Objective
The project's aim is to gather 20 years of real experience with maintenance cost on the most frequently use noise measures (noise barriers, insulation of buildings, track absorbers and acoustic rail grinding), to analyse the replacement costs of noise mitigations measures and hereafter to analyse the financial risks involved.

Please return the filled questionnaire to:

by 15 januari 2012

If there are any questions, please contact:

	Paul de Vos	Paul van der Stap
phone	+31 (0)6-29098228	+31 (0)6-52018688
mail	paul.devos@dhv.com	paul.vanderstap@dhv.com

We thank you for your cooperation!

contact

country	Netherlands			
country code	NL			
region				
name organisation				
postal adress				
zip code				
city				
contact person	name	telephone	fax	e-mail
contact person 1				
contact person 2				
comments				

Tab Existing measures

General information about the network (length, type of lines (main lines/regional lines), traffic, etc). This information may be available from UIC.				
Estimation of total existing network length		km		
			high traffic (>100 trains/day)	low traffic(<100 trains/day)
network characterisation (percentage of network length)				
passenger lines (>75% passengertrains)	40%	0 km	40%	60%
freight lines (>75% passengertrains)	20%	0 km	40%	60%
mixed lines (25%-75% passenger or freight)	30%	0 km	40%	60%
high speed lines	10%	0 km	40%	60%
other	0%	0 km	40%	60%

EXISTING MEASURES	GENERAL				LIFECYCLE COSTS									IMPLEMENTATION PROGRAM
	applied?	estimated number / length [km] / square meters [m2]	unit	average heigth of barriers	unit of cost	procedural cost	investment cost	maintanance cost: annual	maintanance cost: non annual	period of non annual cost (years)	disposal cost	resale value	lifecycle (years)	estimated first year of implementation
Rolling stock & track measures														
retrofitting with composite brake blocks	☑		wagons		€/wagon									
premature scrapping of wagons	☑		wagons		€/wagon									
wheel absorbers	☑		wagons		€/wagon									
track absorbers	☐		km		€/m									
acoustic grinding	☐		km		€/m									
noise barriers per type														
concrete - reflectant	☑		km	2 m	€/m2									
concrete - absorbant	☑		km	2 m	€/m2									
cassette - absorbant	☑		km	2 m	€/m2									
transparant (glass, acrylate)	☑		km	2 m	€/m2									
timber	☑		km	2 m	€/m2									
green barrier with plants	☑		km	2 m	€/m2									
Earth bank	☑		km	2 m	€/m2									
only data available for all types of barriers together	☐													
noise barriers totaal			km	2 m	€/m2									
window insulation per isolation class														
light (0-22 dB: acoustic ventilation system)	☑		houses		€/house									
medium (22-24 dB: light + noise sealing of window, double glazing, new openable window)	☑		houses		€/house									
heavy (>24 dB: medium + roof insulation)	☑		houses		€/house									
only data available for all types of window insulation together	☐													
window insulation total			houses		€/house									

Tab planned measures

General information about the network (length, type of lines (main lines/regional lines), traffic, etc).					
Estimation of total new planned network length (excl. existing network)	3,000	km			
horizon of planned tracks (future year)	2030				
network characterisation (percentage of network length)				high traffic (>100 trains/day)	low traffic(<100 trains/day)
passenger lines (>75% passengertrains)	40%		1200 km	40%	60%
freight lines (>75% passengertrains)	20%		600 km	40%	60%
mixed lines (25%-75% passenger or freight)	30%		900 km	40%	60%
high speed lines	10%		300 km	40%	60%
other	0%		0 km	40%	60%

PLANNED MEASURES	GENERAL				LIFECYCLE COSTS			copy	copy cost from existing LCC					IMPLEMENTATION PROGRAM
	applied?	estimated number / length [km] / square meters [m2]	unit	average heigh of barriers	unit of cost	procedural cost	investment cost	maintanance cost: annual	maintanance cost: non annual	period of non annual cost (years)	disposal cost	resale value	lifecycle (years)	investment program (years from start)
Rolling stock & track measures														
retrofitting with composite brake blocks	☑		wagons		€/wagon									
premature scrapping of wagons	☑		wagons		€/wagon									
wheel absorbers	☑		wagons		€/wagon									
track absorbers	☑		km		€/m									
acoustic grinding	☑		km		€/m									
noise barriers per type														
concrete - reflectant	☑		km	2 m	€/m2									
concrete - absorbant	☑		km	2 m	€/m2									
cassette - absorbant	☑		km	2 m	€/m2									
transparant (glass, acrylate)	☑		km	2 m	€/m2									
timber	☑		km	2 m	€/m2									
green barrier with plants	☑		km	2 m	€/m2									
Earth bank	☑		km	2 m	€/m2									
only data available for all types of barriers together	☐													
noise barriers totaal			km	2 m	€/m2									
window insulation per isolation class														
light (0-22 dB: acoustic ventilation system)	☑		houses		€/house									
medium (22-24 dB: light + noise sealing of window, double glazing, new openable window)	☑ ☑		houses		€/house									
heavy (>24 dB: medium + roof insulation)			houses		€/house									
only data available for all types of window insulation together	☐													
window insulation total			houses		€/house									

Tab distribution and noise limit

Distribution of noise control measures and noise limits

Distribution of noise control measures

	existing		planned	
new lines		%		%
new urban development		%		%
sanitation		%		%
complaint management		%		%
other	100	%	100	%

National Noise limit for railways		dB Lden

Annex 4 Comparative price index EU countries

	2008, EU-27=100	2008, NL=1
EU-27	100	0.97
Euro	104	1.01
Belgium	111	1.08
Bulgaria	51	0.50
Czech	72	0.70
Denmark	141	1.37
Germany	104	1.01
Estonia	77	0.75
Ireland	127	1.23
Greece	94	0.91
Spain	96	0.93
France	111	1.08
Italy	105	1.02
Cyprus	90	0.87
Latvia	75	0.73
Lithuania	67	0.65
Luxembourg	116	1.13
Hungary	70	0.68
Malta	78	0.76
Netherlands	103	1.00
Austria	105	1.02
Poland	69	0.67
Portugal	87	0.84
Romania	62	0.60
Slovenia	83	0.81
Slovakia	70	0.68
Finland	125	1.21
Sweden	114	1.11
UK	99	0.96
Norway	139	1.35
Switzerland	130	1.26

Table 17. Comparative price levels, compared to EU-27=100 and NL=1

(final consumption by private households including indirect taxes, EU-27=100)

Source: Europe in figures / Eurostat yearbook 2010 table 1.13 [14]

Annex 5 Second announcement Questionnaire

From: Stap, Paul vander
Sent: dinsdag 10 april 2012 11:08
To:
Cc:
Subject: questionnaire UIC real cost, final check

Dear mr. ms….,

In the frame of the UIC study into the life cycle cost of various noise mitigation options, DHV has sent out a spreadsheet questionnaire, requesting information on current and future noise mitigation in your network. In many cases it turned out that there was not sufficient information available to fill the questionnaire.

In these cases, we have taken the liberty to fill the spreadsheet ourselves. We started from the current network length, which is generally known. For future extensions (reference year 2030), we added 1% of the current network length (unless we had real data). We used the 2007 UIC report on current and future noise mitigation as background.

For track related measures, we estimated the total length and typical average height of noise barriers in your network.
For rail absorbers, we added a length on the basis of our estimate (in many countries, rail absorbers have not been used at all).
For façade insulation, we added a total number of dwellings on the basis of estimates, both for the current and future situation.

For the cost of these measures, we used detailed information from the NL network. This information was corrected on the basis of the Eurostat price index, which is indicated in the spread sheet.
We did not fill any information on vehicle related measures, as this will be added to the comparison on a full EU basis only.
In addition to this, we checked the National Noise Action Plans for your country for information on future noise mitigation measures for railways.

We kindly request you to check the information in the spreadsheet and send us your corrections if you feel that the numbers estimated by us are significantly deviating from the real values. If you feel that the order of magnitude is correct, there is no need for correction. In that case, please send us your agreement.

We would welcome your reply within the shortest possible delay. If we have not heard from you by 25th April, we will assume that you agree with the data provided.

Thank you very much in advance,

Kind regards,

Paul de Vos
Paul van der Stap

Annex 6 STAIRRS: Collected values for noise reducing measures

measures		Cost per unit[€]	Lifetime per measure[Years]	Maintenance0* [Years]	Frequency** [Years]	Maintenance costs[€]	Source of the data
1.1 Noise barriers	**barrier 2m per m (-10 dB/m)**	810	25	10			UIC
	barrier 3m per m (-15 dB/m)	1 080	25	10			UIC
	barrier 4m per m (-20 dB/m)	1 350	25	10			UIC
	per m²	800					Swiss
		250	30			5	SNCB
Insulated windows	**per house (4 windows)*****	8 000					UIC
		9.000					Swiss
Rolling Stock improvement (freight cars)	**Composite brake blocks - 5 dB**	9 000	40	5			UIC
	Composite brake blocks - 10 dB	9 000	35	5			UIC
	Optimized wheels						
	1.1.1 Per wagon	15 000					Swiss
Rolling Stock improvement (passengers cars)	**Composite brake blocks - 5 dB**						
	Composite brake blocks - 10 dB						
	Optimized wheels						
	Per wagon		15-25				SNCB
		28 000					Swiss
Track improvement	**tuned absorbers (- 5 dB/m)**	200	30	3		2	SNCF
	grinding ****	0	A_{max}	0			

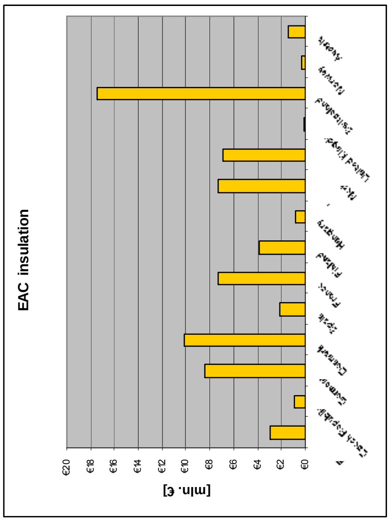
* Maintenance0 is the year when maintenance for the measure *j* begins.
** Frequency at which the maintenance has to be implemented.
*** We consider no maintenance costs for insulated windows
**** Grinding is taken into account as maintenance costs.

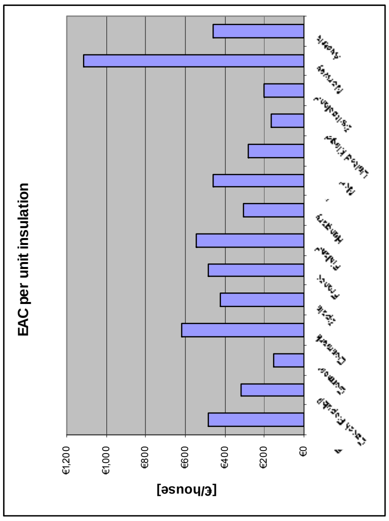
Annex 7 NPV and EAC existing + planned measures, total and per unit measure

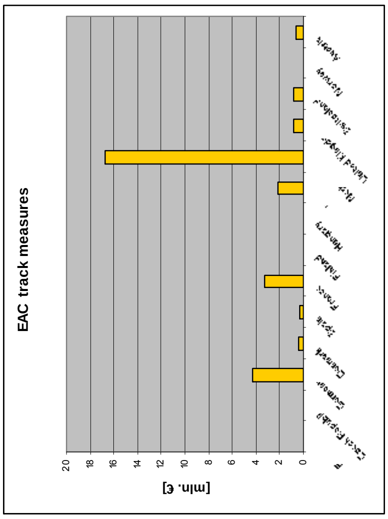
The Net Present Value (NPV) and Equivalent Annual Costs (EAC) for existing and planned measures. On the next page a graphical representation of the data.

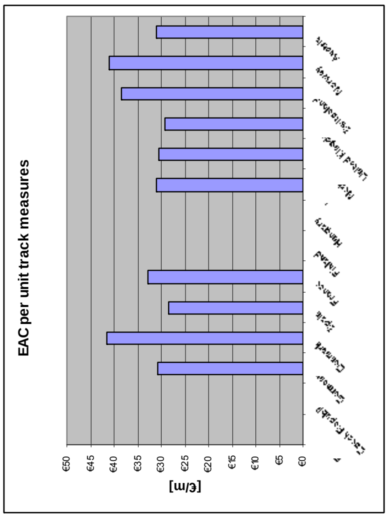
LCC ANALYSIS EU / EXISTING+PLANNED MEASURES / total NPV and EAC in million €											
			track measures			noise barriers			insulation		
code	country	price index	km	NPV	EAC	km	NPV	EAC	houses	NPV	EAC
BE	Belgium	1.08	0.0	0.0	0.0	150.0	324.7	11.7	6000.0	97.0	2.9
CZ	Czech Republic	0.70	0.0	0.0	0.0	130.0	183.1	6.6	3000.0	31.5	0.9
DE	Germany	1.01	140.0	74.9	4.3	1350.0	3122.3	112.8	56000.0	279.5	8.4
DK	Denmark	1.37	10.0	7.3	0.4	90.0	218.0	7.9	16500.0	338.8	10.2
ES	Spain	0.93	10.0	4.9	0.3	280.0	468.3	16.9	5000.0	69.9	2.1
FR	France	1.08	100.0	57.1	3.3	330.0	714.3	25.8	15000.0	242.5	7.3
FI	Finland	1.21	0.0	0.0	0.0	70.0	169.8	6.1	7000.0	127.4	3.8
HU	Hungary	0.68	0.0	0.0	0.0	60.0	82.2	3.0	2500.0	25.5	0.8
IT	Italy	1.02	70.0	37.8	2.2	550.0	1641.8	59.3	16000.0	244.7	7.4
NL	Netherlands	1.00	549.1	290.8	16.7	1519.5	3234.2	116.9	24347.0	229.4	6.9
UK	United Kingdom	0.96	28.0	14.3	0.8	38.0	68.7	2.5	500.0	2.8	0.1
CH	Switzerland	1.26	20.0	13.4	0.8	461.1	1207.1	43.6	85689.0	579.3	17.4
NO	Norway	1.35	0.5	0.4	0.0	60.0	180.2	9.2	300.0	7.7	0.3
AU	Austria	1.02	20.0	10.8	0.6	500.0	1026.2	37.1	3000.0	45.9	1.4

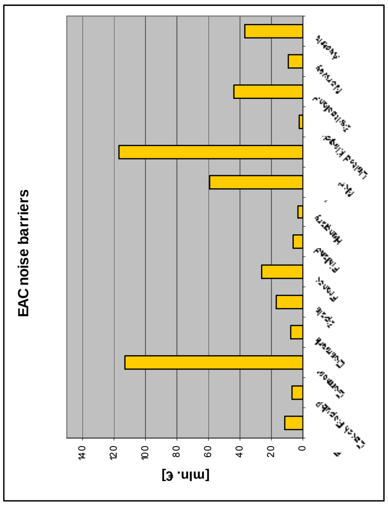
LCC ANALYSIS EU / EXISTING+PLANNED MEASURES / NPV and EAC per unit measure [€]											
			track measures			noise barriers			insulation		
code	country	price index	km	NPV	EAC	km	NPV	EAC	houses	NPV	EAC
BE	Belgium	1.08	0	0.0	0.0	30	64.9	2.3	2000	32.3	1.0
CZ	Czech Republic	0.70	0	0.0	0.0	15	21.1	0.8	1500	15.7	0.5
DE	Germany	1.01	0	0.0	0.0	300	936.7	33.8	10000	151.5	4.6
DK	Denmark	1.37	10	7.3	0.4	20	27.3	1.0	6500	133.5	4.0
ES	Spain	0.93	10	4.9	0.3	130	297.0	10.7	2000	28.0	0.8
FR	France	1.08	50	28.5	1.6	30	64.9	2.3	5000	80.8	2.4
FI	Finland	1.21	0	0.0	0.0	10	24.3	0.9	3000	54.6	1.6
HU	Hungary	0.68	0	0.0	0.0	10	13.7	0.5	1000	10.2	0.3
IT	Italy	1.02	50	27.0	1.6	500	1539.2	55.6	8000	122.3	3.7
NL	Netherlands	1.00	450	238.3	13.7	1100	2428.7	87.8	10000	150.0	4.5
UK	United Kingdom	0.96	28	14.3	0.8	33	59.6	2.2	500	2.8	0.1
CH	Switzerland	1.26	20	13.4	0.8	113	384.7	13.9	61300	414.4	12.5
NO	Norway	1.35	0	0.0	0.0	10	30.0	1.5	200	5.1	0.2
AU	Austria	1.02	0.0	0.0	0.0	50	102.7	3.71	1000	15.3	0.46

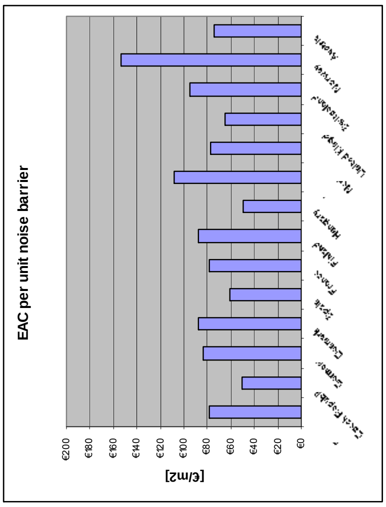

EAC insulation
[mln. €]


EAC per unit insulation
[€/house]


EAC track measures
[mln. €]


EAC per unit track measures
[€/m]


EAC noise barriers
[mln. €]


EAC per unit noise barrier
[€/m2]

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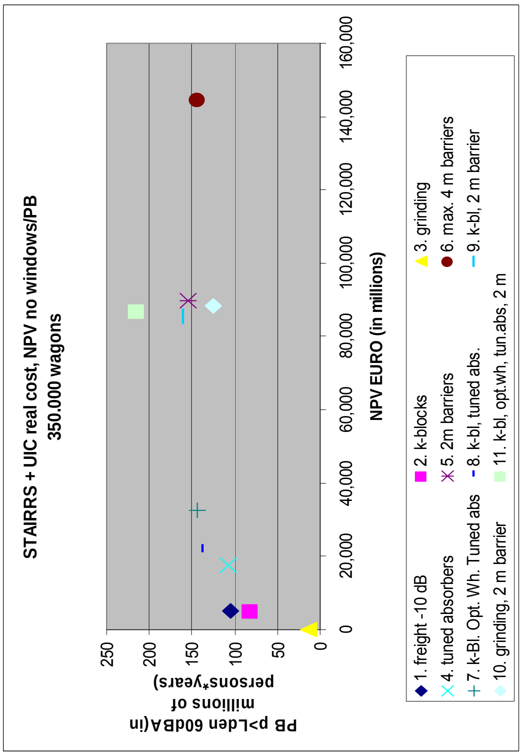
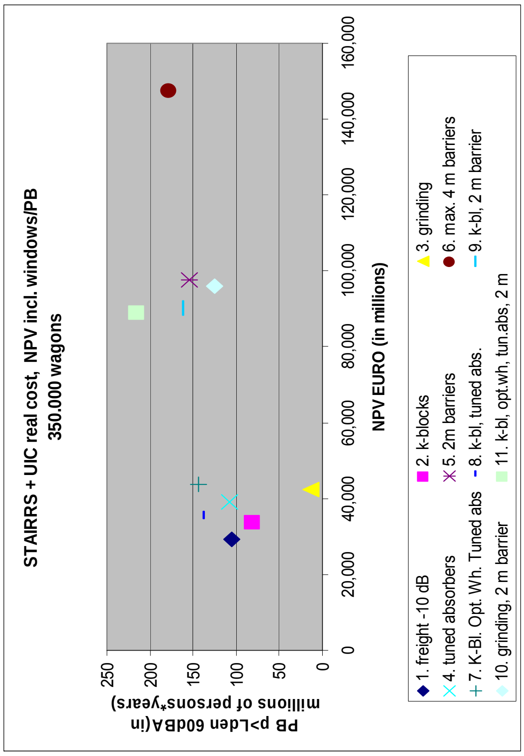
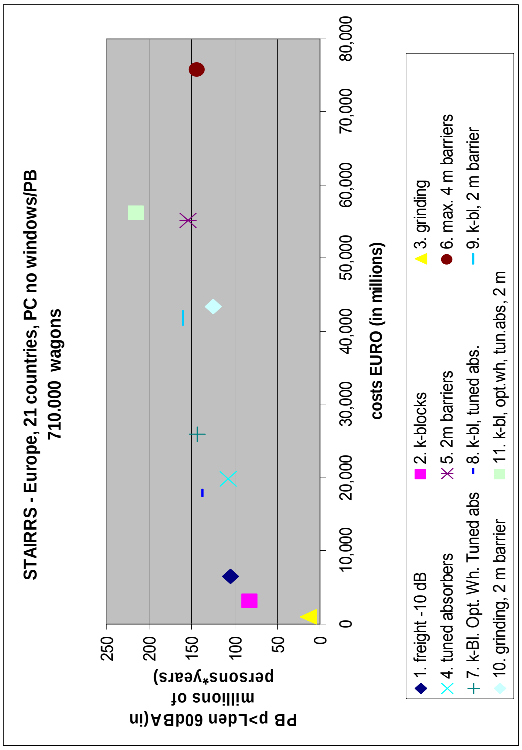
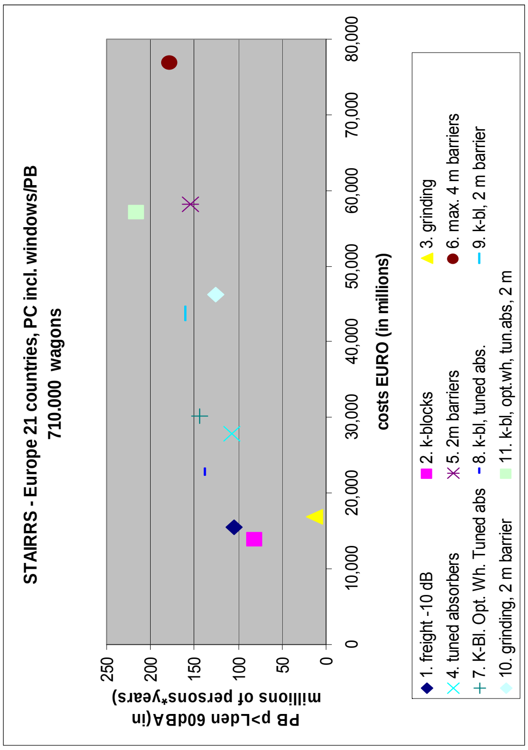
Annex 8 updated STAIRRS figure compared with original figure









Annex 9 Barrier categories

Shapes	*Material*	*Sound Absorption*	
		type of absorption	*type of absorptive material*
a. plane, vertical b. plane, inclined c. plane, curved d. plane, bent e. embankment	A. metal B. concrete C. brick or ceramic D. wood or board E. transparent glass or plastic F. earth	1. no absorption 2. integrated absorption 3. additional absorption	a. rock or mineral wool b. glass wool c. chip wood d. clay grains or other ceramic granulate e. plastic or rubber foam.

Barrier categories