Options for reducing noise from roads and railway lines

Kurt Heutschi*

Empa, Swiss Federal Laboratories for Materials Science and Technology, Duebendorf, Switzerland

Erik Bühlmann*

Grolimund + Partner AG environmental engineering, Bern, Switzerland

Jakob Oertli*

SBB, Swiss Federal Railways, Bern, Switzerland

Abstract

The fundamental noise generation mechanisms of road and rail vehicles are discussed with attention to noise abatement measures. Based on an evaluation of publicly available tire noise data and the European road traffic noise emission model CNOSSOS, it is shown that on the road side there is a significant noise reduction potential in the usage of low-noise tires. From a three months measurement campaign a noise model was derived to predict the maximal sound pressure level of heavy duty vehicles during a pass-by in 7.5 m distance with the parameters vehicle speed and number of axles. With help of recently published information about external costs caused by heavy duty vehicles and the noise prediction tool, a model was developed to derive a money equivalent that can be used as a bonus/malus in a heavy duty vehicle fee. As a measure at the infrastructure, the installation of low-noise pavements is an effective, durable and economically attractive measure. Recent experiences with different technologies from all over the world are compiled and evaluated. On the rail side, an overview of the possible noise reduction strategies is given, followed by a discussion of the current policy and legislation in the EU and on the national

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*Corresponding author

Email address: `kurt.heutschi@empa.ch` (Kurt Heutschi)

level of different European countries.

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Highlights

- estimation of noise reduction potential of low noise tires and low noise road pavements
- model to allocate noise reduction to costs
- compilation of noise abatement strategies for railway lines
- discussion of the current policy and legislation for railway lines in the EU and on the national level of different European countries

1. Introduction

Transport of goods, either on road or on rail, interferes with the environment. The parameters to describe the environmental footprint of a road and rail vehicle were identified in the Eureka project Footprint (2001 to 2008), see refs. [1], [2]. Based on monitoring measurements and theoretical investigations it was found that the aspects

- static and dynamic loading
- audible noise
- gaseous and solid pollutants

are most relevant. In the ongoing Ecovehicle project, data analysis methods will be developed to identify vehicles with abnormal parameter values [3]. Strategies are developed to inform drivers and operators about the unusual condition of individual vehicles. Furthermore, appropriate criteria will be developed to characterize environmentally friendly road and rail vehicles. In a final step a relation between environmental impacts and costs will be established in order to determine an incentive (bonus) for vehicles with a low footprint and a penalty (malus) for vehicles with a large footprint. This would allow for the constitution of a *polluter pays principle* as aimed for in the EU Green Transport package of 2008.

This paper focuses on the noise aspects of the environmental footprint of road and rail vehicles. Many studies have shown, that environmental noise and especially transportation noise has very negative effects on health of humans. Noise can cause annoyance, cardiovascular problems, sleep disturbance and cognitive impairment of children. Due to the relevance of the problem, the European Council has enacted the Environmental Noise Directive (END) [4] in 2002 for the reduction of environmental noise. On one hand END initiated the development of an EU-wide collection of noise maps, on the other hand the member states are obliged to design action plans to limit and lower traffic noise. In [5] a tool has been presented to support the evaluation and prioritization of possible technical measures.

Noise exposure of residents depends on the source strength and the propagation attenuation from source to receiver. Sound propagation attenuation is strongly influenced by obstacles that interrupt the sightline. The installation of artificial barriers is an effective method to significantly lower noise exposure. However, acceptance is generally limited due to disturbance of the visual impression. In urban environments only noise barriers of low height are an option, however under specific circumstances they prove to be surprisingly efficient [6], [7]. As the sound field in an urban situation is heavily influenced by reflections at building facades, the shape and form of the street canyons play an important role [8].

The source strength of traffic noise emission can be lowered by measures taken at the infrastructure or at the individual vehicle. As will be shown later in the paper, great efforts have been made over the last twenty years to reduce road traffic noise by specifically designed pavements. Railway noise reduction on the side of the infrastructure can be achieved by rail grinding to smoothen the tracks and rail damping to absorb vibrational energy. Both on road and rail there is a pronounced spread of the emission of individual vehicles [9]. From the view of the authorities, it seems therefore interesting to seek for incentives to motivate vehicle owners to reduce the emission of the individual vehicle. As will be shown later, this can be achieved by low noise tires on one hand and by low wheel roughness due to favorable braking systems on the other hand.

The paper is organized as follows: it starts with a discussion of the fundamental noise generation mechanisms and the consequences for noise control at the source. Section 2 is dedicated to road vehicles, Section 3 addresses rail vehicles. Finally in Section 4 conclusions are drawn with emphasis on possibilities on how politics can motivate for quieter vehicles with help of pricing systems.

2. Quieter roads

2.1. Noise emission of road vehicles

Noise emitted by road vehicles is broadband in its spectral contents with two peaks around 60 and 800 Hz (see Figure 1). It can be split up into a contribution of the tire/pavement interaction (rolling noise) and a contribution of the engine and the exhaust system (propulsion noise). Rolling noise depends mainly on vehicle speed, the number of axles, the tire and pavement properties and the temperature. Propulsion noise is determined by the configuration of the engine and the exhaust system and by the condition of the engine, that is to say the rotational speed of the engine and the engine load. Within a specific vehicle category and for a typical driving style, a relation between vehicle speed, grade of the road, acceleration/decceleration and engine noise can be established.

With help of emission models e.g. [10],[11], sound radiation by single vehicles can be predicted. As a descriptor the acoustically radiated sound power is used.

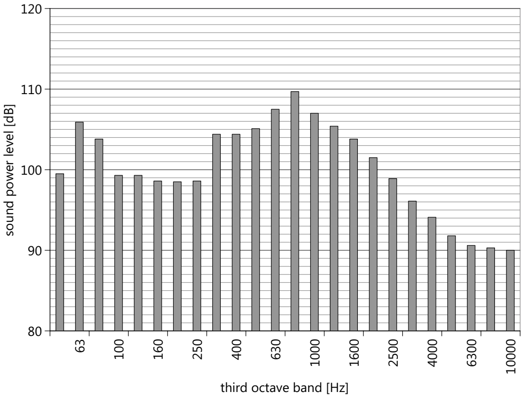

Figure 1: Measured third octave band spectrum of sound power emitted by a heavy duty vehicle at 88 km/h.

With 19 May 2015 the EU has published in the directive 2015/996 a common noise assessment method (CNOSSOS) [12] to harmonize noise calculation in the member states. At least for reporting to the Commission, all member states have to use CNOSSOS by end of 2018. Figure 2 and 3 show the speed dependencies of rolling and propulsion noise for the two vehicle categories *passenger cars* and *heavy vehicles*. The speed dependent sound power levels in Figure 2 follow directly from the CNOSSOS formulas. In Figure 3 rolling noise and propulsion noise levels are converted to a linear scale and presented as fraction of total noise. At low vehicle speeds, propulsion noise dominates while rolling noise is most relevant at higher speeds. According to CNOSSOS, the speeds for equal contribution are 30 km/h for passenger cars and 75 km/h for heavy vehicles. It should be noted that the curves shown in Fig. 2 and 3 are valid under normal driving conditions. If the car is operated at high revs, propulsion noise is significantly higher.

Depending on the vehicle category and the speed regime either the reduction of rolling noise or propulsion noise is the most effective noise abatement strategy. Rolling noise can be lowered by application of low noise tires and or the installation of low noise road pavements. A reduction of propulsion noise

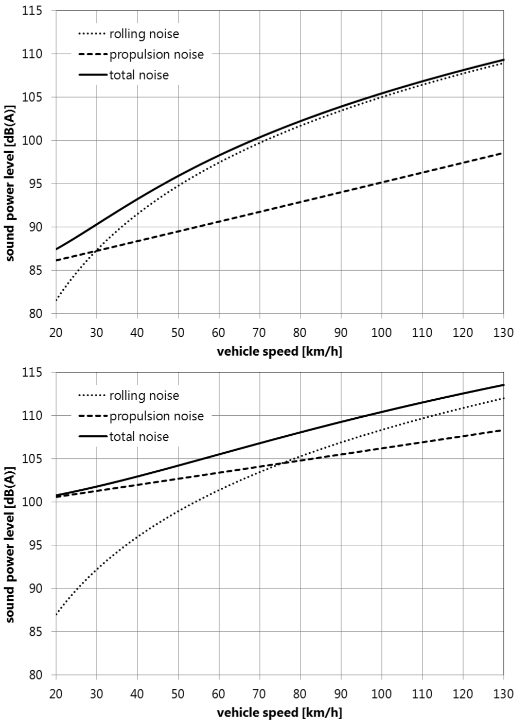

Figure 2: A-weighted sound power level of rolling noise, propulsion noise and total noise for passenger cars (left) and heavy vehicles/trucks (right) under reference conditions according to the road traffic noise emission model in CNOSSOS [12].

of combustion engines can be achieved by enclosing the engine. While this is standard for passenger cars there is a large potential in engines of heavy vehicles. A very rigorous strategy to get rid of propulsion noise is the installation of electrical drive systems. An additional benefit of these systems is the prevention of high revs driving conditions.

In the following, the aspects of low noise tires (Section 2.2) and low noise pavements (Section 2.3) will be discussed in more detail. Finally we will reflect about a noise dependent heavy duty vehicle fee that might support the introduction of low noise tires in heavy vehicles.

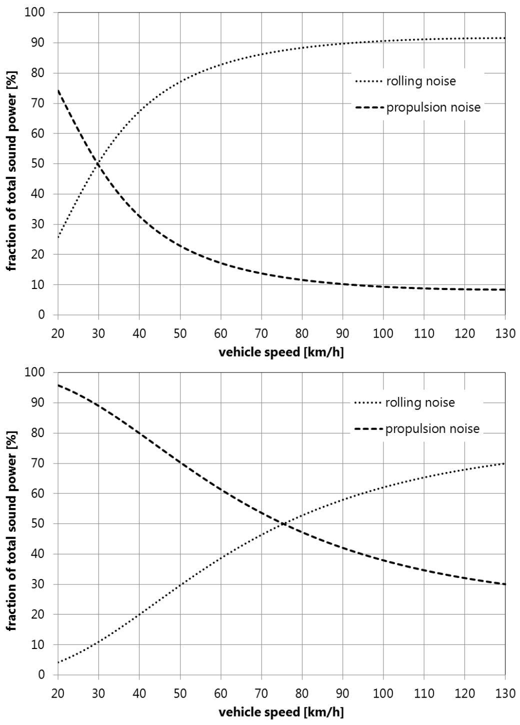

Figure 3: Rolling noise and propulsion noise expressed as percentage of total noise for passenger cars (left) and heavy vehicles/trucks (right) under reference conditions according to the road traffic noise emission model in CNOSSOS [12].

2.2. Tire label

With the regulation 1222/2009, the EU introduced in 2012 a label to characterize the properties of individual tires. It displays important information about safety and environmental aspects of a tire. It allows comparing tires in terms of fuel efficiency, wet grip and noise. Noise is specified as maximum pass-by sound pressure level in 7.5 m distance. In addition to the indication of the level [dB(A)], an allocation to one of three noise classes is also shown for a quick and easy interpretation. For the first time, customers that wish to buy low noise tires have access to the necessary information.

2.2.1. Statistical analysis of available tires

In order to analyze the noise properties of current tires, data of commercially available tires in Central Europe were collected. Information about tires for passenger cars was obtained from the data collection *Reifenettikette* (www.reifenetikette.ch) an initiative of FOEN (Federal Office for the Environment, Switzerland). For tires for heavy vehicles the database of a large online vendor: http://www.reifendirekt.ch/LKW-Reifen.html was utilized (data download August 2014). In this way data of 10'000 tires for passenger cars and data of 530 tires for heavy vehicles was evaluated. Heavy vehicle tires are differentiated according to their use as *driving axle tires*, *front axle tires* and *trailer tires*. It should be noted that the absolute emission values of passenger car and truck tires can't be compared as they are measured according to slightly different procedures.

tire type	median	25% quantile	75% quantile	min	max
passenger car summer	71	70	72	65	78
passenger car winter	71	70	72	65	77
truck driving axle all season	75	74	76	70	79
truck driving axle summer	76	73	76	70	78
truck driving axle winter	74	73	75	68	78
truck front axle summer	71	70	73	67	76
truck front axle winter	73	73	73	72	76
truck trailer all season	70	70	72	69	76

Table 1: Statistical parameters in dB(A) for the different tire categories. median, 25% quantile and 75% quantile indicate the values that separate the lower half, the lower quarter and the upper quarter from the rest of the data sample. min/max represent the lowest and highest values found.

The analysis of all data reveals statistical descriptors for the different tire categories as shown in Table 1. In contrast to conventional wisdom, today's winter tires for passenger cars are not noisier than summer tires. However seasonal differences in emission strength may occur due to systematic temperatures differences. As the tires become stiffer with lower temperatures, noise emission is slightly higher during the cold season. Figure 4 shows in a xy-plot the relation between passenger car tire width and noise level. Although there is a clear correlation between the two quantities there is a large spread between the most silent and the noisiest tire for a specific width. In addition, relations were examined between the fuel consumption category and noise as well as the wet grip category and noise. With $R^2 < 0.03$ in both cases no significant correlation between these quantities was found. Consequently a silent tire has not necessarily bad properties in the other aspects.

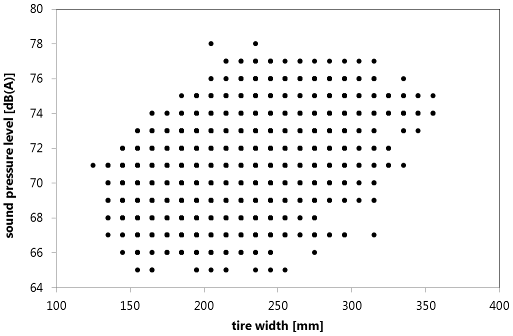

Figure 4: xy-plot showing tire label noise values of passenger car tires (y-axis) as a function of tire width (x-axis).

For truck tires, on average, driving axle tires are around 3 dB(A) noisier than front axle tires and 5 dB(A) noisier than trailer tires. The span between the 25% and the 75% quantile is generally quite small, that is to say the majority of the tires in a specific category has very similar emission values. However in most cases there is a significant difference between the median and the minimum value. This suggests that a substantial noise reduction potential lies in the suitable choice of the tire. Figure 5 shows the total noise reduction for a -3dB(A) (with respect to average) tire under the assumption that the rolling noise reduction does not depend on speed. The calculations were performed based on the noise emission model from CNOSSOS [12]. In case of passenger cars, total noise is significantly lowered already at urban speed regimes while for trucks the effect becomes relevant at highway speeds only. It can be concluded that low noise tires exhibit a significant noise abatement potential.

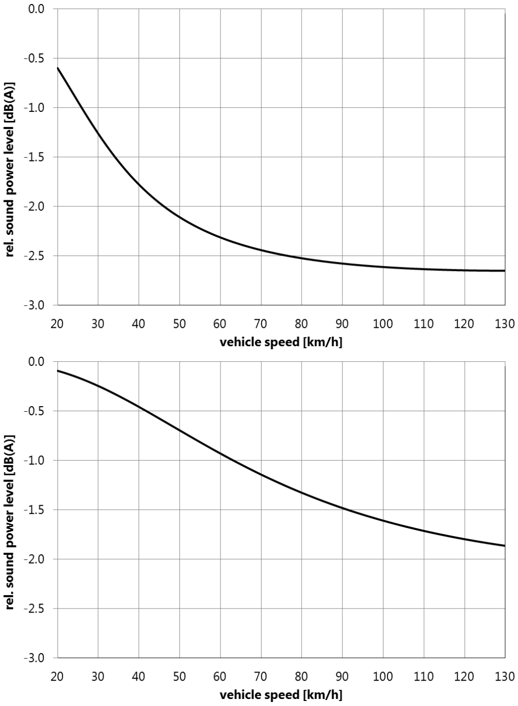

Figure 5: Total A-weighted sound power level modification by usage of tires with 3 dB(A) lower emission than average. Left: passenger cars, right: heavy vehicles/trucks.

2.3. Low noise road pavements

Low-noise road pavements have become a popular and widely used measure in many western countries to reduce road traffic noise at its source. The development of effective and durable noise reducing pavements remains a challenge, since the acoustic objectives are often in conflict with some of the primary functions of a pavement's wearing surface, namely: to provide adequate surface friction and texture i.e. skid resistance as well as to protect the sub-layers and the supporting structure from water, mechanical forces and the axle loads by providing sufficient structural capacity [13]. Failure to meet these primary functions may lead to safety issues or to premature failure of the pavement. Recently, several countries have developed new innovative low noise pavement solutions as part of national and cross-boundary noise abatement policies and programs.

2.3.1. FEDRO Study

In a recent project funded by the Swiss Federal Roads Office (FEDRO), the practical experience with these various innovative technologies was drawn together and assessed [14]. As part of this project, a series of expert interviews with the leading international actors was carried out in order to evaluate and cross-compare the performance of the innovative technologies regarding important aspects such as the total achieved noise reduction, cost-benefit, feasibility, traffic safety, acoustic durability, ease of maintenance and costs. For cross-comparison purposes, a ranking scheme was developed for each of these aspects and a mean cost-feasibility-maintenance score was calculated. The score equally weights the pavements performance regarding cost, feasibility and maintenance, while applying a general safety criterion for inclusion. More details on the technologies and their specific performance as well as on the calculation procedure for the *c/f/m score* can be found in [14]. An up-to-date selection of the low-noise pavement solutions currently considered as most promising by the leading actors is given below, labeled with a *c/f/m score* that indicates the mean value of cost, feasibility, and maintenance scores (with conventional pavements as a reference). As a reading example, the *c/m/f score* of 100 % would mean that the low-noise pavement:

- costs the same (or less) than conventional pavements (concerns construction costs)
- is (at least) as ”easy” to construct as conventional pavements, i.e. that

its construction does not require special materials, special processing facilities, special construction equipment or rarely available specialist know-how. Longer installation time in comparison to conventional pavements and special requirements regarding meteorological conditions during construction would also lead to a discount in the score.

- does not require special maintenance, e.g. regarding cleaning, repair or winter maintenance.

List of pavement solutions:

- 1, CH: SDA 4, Semi-dense asphalts with 4 mm chipping size, target void contents in the bituminous mixture 12 and 16%. Designed for low speed roads in urban areas. Small granulate size and very fine pores are to prevent water and dirt from entering the pores and clogging the pavement. The lower void content in comparison with porous pavements intends to improve the durability of the pavement while still enabling absorption and other low-noise properties. *c/f/m score: 73%.*
- 2, CH: SDA 8, Semi-dense asphalts with 8 mm chipping size and target void contents in the bituminous mixture between 12 and 16% is designed for low and high speed roads with increased mechanical strains. *c/f/m score: 73%.*
- 3, CH: ACMR 8, Split mastic asphalt with chipping size 8 mm and increased void content (6 to 10%). Noise reduction is mainly achieved by reducing air-flow noise with its rugous surface texture. *c/f/m score: 81%.*
- 4, D: LOA 5 D, Noise optimized surface layer to provide high stability and resilience of the surface texture obtained by a low void content. Void content 5 to 7%, chipping size = 5 mm, layer thickness 20 to 30 mm. *c/f/m score: 83%.*
- 5, D: PMA 5, Porous Mastix Asphalt is based on adapted mastic asphalt mixture with a higher percentage of coarse aggregates and a lower content

of bitumen. The bitumen settles between the course aggregates and creates to some degree a porous surface. It is applied as a water sealing layer. *c/f/m score: 77%.*

- 6, D: SMA LA 8, Split mastic asphalt with improved noise reducing features obtained by a different grading line than the conventional SMA. This split mastic asphalt does not have any connected pores but a pronounced plateau-ravine-system resulting in an improved acoustic effect. Void content 12%, chipping size 8 mm. *c/f/m score: 85%.*
- 7, DK: PERS 5 DK, Poro-elastic road surface with the use of old tire material as the main aggregate. Noise reduction is provided by porosity and mechanical impedance. Void content 26 to 30%, chipping size 5 mm. *c/f/m score: 28%.*
- 8, DK: SMA 6 + 8 / SMA 6 + 11, Further development of a conventional split mastic asphalt with improved mechanical resilience by adding oversize aggregates in small numbers. Void content 7 to 9%, chipping size 6+8/11 mm, layer thickness 20 to 30 mm. *c/f/m score: 94%.*
- 9, F: VTAC 0/6, Very Thin Layer with a chipping size 6 mm. Acoustic effect and optimized grip. Fast and simple construction procedure. Void content 12 to 20%, layer thickness 20 to 30 mm. *c/f/m score: 88%.*
- 10, JP: Double Layer PA, Improved noise reduction compared to single-layer porous asphalt pavements. Base layer: chipping size 13 mm, layer thickness 30 mm; top layer: chipping size 5 mm, layer thickness 20 mm. *c/f/m score: 46%.*
- 11, JP: PERS 2 JP Poro-elastic road surface with the use of old tire material as the main aggregate. Noise reduction is provided by porosity, very fine texture and mechanical impedance. Void content $>$ 30%, chipping size 2 mm. *c/f/m score: 25%.*

- 12, NL: Diffractors, Concrete elements placed next to the lane deflecting the noise upwards and creating a noise shadow zone. Diffractors can be combined with low-noise pavements to increase overall noise reduction. *c/f/m score: 27%.*

- 13, NL: Measures to prolong lifetime, Preventative application of a bituminous emulsion to prolong the lifetime of a thinlayer and porous low-noise pavement. Applied on average 5 to 7 years after installation as first rutting appears. Prolongs lifetime up to 4 years. *c/f/m score: 65%.*

- 14, NL: Modieslab - Porous Beton, Two different concrete slabs with open pores on reinforced concrete sub-base with design focus on technical and acoustic durability. *c/f/m score: 40%.*

- 15, NL: SMA 8 G+, Split mastic asphalt with low-noise properties. Void content 8 to 10%, grains size 8 mm, layer thickness 35 mm. Focus on durability. *c/f/m score: 73%.*

- 16, NL: Thinlayer NL, Thin surface layer with a high noise reduction provided by the open structure in connection with an ideal surface layer structure. Layer thickness 25 mm. *c/f/m score: 73%.*

- 17, NL: Ultrastil, Further development of poro-elastic road surfaces with focus on very high noise reductions while improving durability. Minimum target void content of 15%. *c/f/m score: 19%.*

- 18, SE: PERS 2-5 SE, Poro-elastic road surface with the use of old tire material as the main aggregate. Noise reduction is provided by mechanical impedance. Void content 20%, chipping size 2 to 5 mm, layer thickness 30 mm. *c/f/m score: 28%.*

- 19, SE: Epoxy, The bonding agent additives lead to a reduction of grain outbreak and less mechanical damage resulting in greater durability of noise optimized surface layers. *c/f/m score: 46%.*

- 20, USA: Diamond grinding, Optimizing the surface texture of cement concrete pavements by grinding close-spaced furrows in longitudinal direction on new and existing cement concrete surface. Increases safety as well as reducing tire/road-noise. *c/f/m score: 81%.*

- 21, USA: Longitudinal tining, Acoustically optimized modification of the surface layer by applying a texture in longitudinal direction with a rake on new cement concrete surface layers. *c/f/m score: 88%.*

The recent approaches regarding development and application of low-noise pavement solutions world-wide can be categorised into three main strategies which are further described below.

2.3.2. Strategy with focus on maximizing noise reduction

Probably the most frequent approach focusses on technological solutions maximizing the total noise reduction achieved by the innovative pavement. This involves the development of pavements with, for instance, higher void content (to improve sound absorption properties and reduce air-pumping noise), finer texture and aggregate size (to reduce vibration noise) and adding special materials to the mixtures in order to increase the mechanical impedance of the pavement (to reduce low-frequency vibration noise). The aim is to realize large noise reductions and thereby protect those people in densely populated areas where road traffic noise substantially exceeds hazardous levels or legal limits. In some cases negative side-effects of these surfaces such as a lower acoustic and technical durability or high construction costs are offset by costs saved due to the avoidance of other more expensive mitigation measures such as sound proof windows, noise barriers or tunnels. Figure 6 shows the performance of low-noise pavements available worldwide with regard to noise reduction in their new state (a few months after construction). Noise reduction is calculated by comparing the pavements' acoustical properties to those of conventional SMA 11 road pavements, a pavement widely used in Europe and North America.

As Figure 6 illustrates, there are several low-noise pavements available with

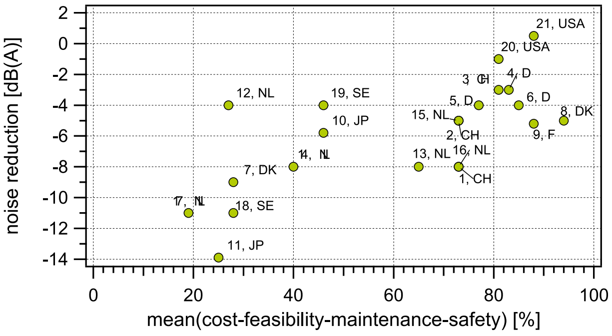

Figure 6: Low noise pavements and their performance regarding noise reduction together with their c/f/m score. A score of 100 % signifies that the low-noise pavement possesses on average the same or better characteristics regarding cost, feasibility, and maintenance than conventional pavements. Noise reduction and c/f/m score are derived from expert interviews.

a high performance regarding noise reduction in their new state. Technologies achieving extremely high noise reductions, however, seem to perform less well in the cost-feasibility-maintenance score. This indicates that too great a focus on maximising acoustic performance may compromise the other functions of a low-noise pavement.

2.3.3. Strategy with focus on acoustic and technical durability

When developing noise-reducing pavements, often compromises need to be made between the acoustic objectives, i.e. maximizing noise reduction, and the primary functions of a pavement. This second strategy seeks to find an optimum balance between these different and contrasting objectives and in this case accepting lower noise reduction performance while enabling greater acoustic and technical durability. Figure 7 shows the performance of low-noise pavements available worldwide with regard to their acoustic and technical durability. Durability is expressed in years and refers to the time until a pavement loses its noise reduction properties (in comparison to a conventional SMA 11 road pavement) or until the pavement reaches the end of its technical lifetime. This figure is either based on practical experiences or, if not available, on extrapolations of existing data.

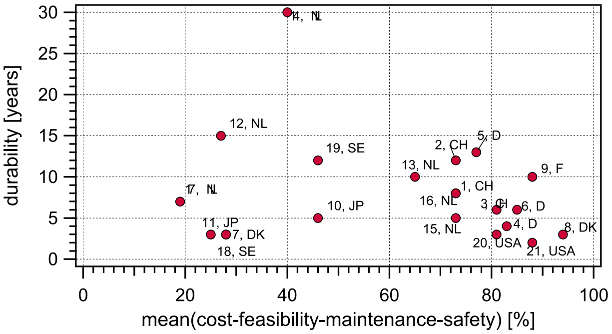

Figure 7: Low noise pavements and their performance regarding acoustic and technical durability (time until a pavement loses its acoustical properties or stops fulfilling its primary functions) together with their c/f/m score. A score of 100 % signifies that the low-noise pavement possesses on average the same or better characteristics regarding cost, feasibility, and maintenance than conventional pavements. Durability and c/f/m score are derived from expert interviews.

Figure 7 shows that high durability of low-noise pavements is difficult to obtain. Only 7 out of 21 technologies achieve a durability of 10 years or more. In many cases, this time period may constitute the minimum requirement for the durability of a low-noise pavement in order to be a cost effective measure. Further innovation with focus on durability is still needed in order to increase the number of durable low-noise pavement solutions.

2.3.4. Strategy with focus on cost-benefit

This third strategy focusses on achieving a noise reduction whenever a good cost-benefit ratio can be obtained. This strategy involves improving the acoustic properties of existing pavement types with innovative adaptations without substantially increasing the costs of the technology. Figure 8 shows the performance of low-noise pavements available worldwide regarding a cost-benefit criterion expressed in USD per dB(A) in noise reduction. The cost-benefit criterion relates to the additional costs for a low-noise pavement (in comparison with a conventional pavement) per m^2 of constructed pavement and the noise reduction achieved by the pavement.

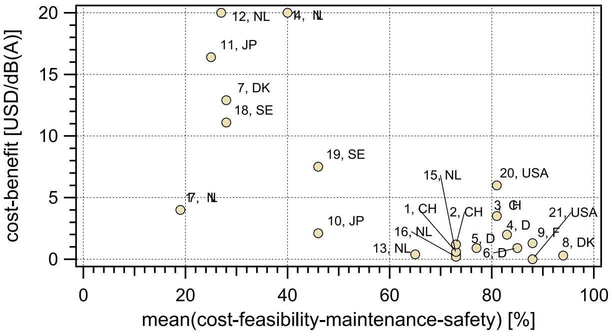

Figure 8: Low noise pavements and their performance regarding a cost-benefit criterion in USD/dB(A) together with their c/f/m score. A score of 100 % signifies that the low-noise pavement possesses on average the same or better characteristics regarding cost, feasibility, and maintenance than conventional pavements. Cost-benefit ratio and c/f/m score are derived from expert interviews.

Figure 8 shows that reasonably good cost-benefit ratios of < 5 USD/dB(A) are obtained for roughly two third of the assessed technologies. Low noise pavement solutions with higher cost-benefit ratios require further technological improvement with focus on either the cost or the noise reduction performance side.

Evaluating the technologies available worldwide with regard to these three strategies it can be concluded that low-noise road pavements can constitute an effective, durable and economically attractive noise abatement measure at the source. More efforts should be undertaken to better integrate the acoustic objectives with the objectives related to the primary functions of a pavement.

2.4. Noise dependent heavy duty vehicle fee

Road access charges for heavy duty vehicles allow for the promotion of environmental friendly technology. With the introduction of Euro VI engines, gaseous emissions are down at very low levels. As in a few years the majority of heavy vehicles will be equipped with Euro VI engines anyhow, there is no need to further promote this technology with incentives. An evaluation of external costs caused by heavy duty vehicles [15] has shown that the next relevant environmental aspect is noise. For that reason, Switzerland is evaluating a noise dependent heavy duty vehicle fee. The constitution of such a fee requires either a set of in-situ measurement stations that monitor each vehicle and label it according to its noise emission [16] or a noise prediction model that allows for an estimation of emitted noise based on few vehicle specific parameters. For transparency reasons and in order to increase acceptability it was decided to explore the prediction model based solution.

2.4.1. Noise model for heavy duty vehicles

As shown in Figure 2, noise emitted by heavy vehicles is dominated by the contribution of the engine at lower speeds while rolling noise is more relevant at high speeds. Under the assumption that the largest portion of the mileage is generated on highways at speeds between 80 and 90 km/h, a noise model as a basis of a heavy duty vehicle fee has to focus on rolling noise. As the interaction of each tire with the road surface contributes to rolling noise, the number of axles is an obvious parameter that should be considered in a noise model. In addition, the noise properties of the tires in use are of relevance.

Based on three months measurements performed at a highway near Oberbuchsiten in Switzerland [2] an emission model as shown in Eq. 1 was derived. The $\lg(n+1)$ term considers the fact that the emission of a driving axle is higher than the one of a front or trailer axle (Table 1). $30 \cdot \lg(v)$ represents a typical speed dependency of total noise of heavy duty vehicles [12].

$$L_{\mathsf{max,total}} = A_i + E_i \cdot \lg(n+1) + 30 \cdot \lg\left(\frac{v}{v_{\mathsf{ref}}}\right) \tag{1}$$

where $L_{\mathsf{max,total}}$ is the maximal sound pressure level captured in a distance of 7.5 m at a height of 1.2 m, A_i and E_i are model parameters to be determined for each vehicle category i, v is vehicle speed (65 km/h $< v <$ 95 km/h) with $v_{\mathsf{ref}} = 80$ km/h.

vehicle category	A_i	E_i	$n_{50\%}$
freight trucks	82.4	8.4	2.0
freight trucks with trailers	82.8	7.6	3.7
articulated freight trucks with semi-trailers	84.4	5.2	3.9

Table 2: Parameter setting of the noise emission model (Eq. 1) for best fit with measurements. $n_{50\%}$ is the median value of the number of axles as observed in each category.

To account for the effect of tire specific properties as indicated on the tire label, the relative contributions of tire and engine noise have to be considered. According to the CNOSSOS noise model, total emission of heavy vehicles at a speed of 80 km/h splits up into 43% propulsion noise and 57% tire noise. From this follows Table 3, illustrating the relation between tire noise modification and effect on total noise.

ΔL_{tire} [dB(A)]	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
$\Delta L_{\mathsf{max,total}}$ [dB(A)]	-1.9	-1.7	-1.3	-0.9	-0.5	0	+0.6	+1.2	+1.8	+2.5	+3.3

Table 3: Effect of tire noise modification ΔL_{tire} in dB(A) on total noise $\Delta L_{\mathsf{max,total}}$ of heavy vehicles at 80 km/h.

The relation between tire noise modification ΔL_{tire} and total noise variation $\Delta L_{\mathsf{max,total}}$ from Table 3 can be approximated with sufficient accuracy by Eq. 2.

$$\Delta L_{\mathsf{max,total}} \approx 0.0272 \cdot \Delta L_{\mathsf{tire}}^2 + 0.53 \cdot \Delta L_{\mathsf{tire}} \tag{2}$$

Including the individual tire effect in the model from Eq. 1 yields

$$L_{\mathsf{max,total}} = A_i + E_i \cdot \lg(n+1) + 30 \cdot \lg\left(\frac{v}{v_{ref}}\right) + 0.0272 \cdot \Delta L_{\mathsf{tire}}^2 + 0.53 \cdot \Delta L_{\mathsf{tire}} \tag{3}$$

2.4.2. Allocation of noise to costs

It was found in [17] that within a vehicle category, emitted noise is only weakly dependent on vehicle weight. Therefore, from an acoustical point of view, a pricing system should be based on vehicle kilometers and ignore weight. In fact, heavy vehicles that can carry higher loads usually have more axles that lighter vehicles. Weight is therefore indirectly considered by a model that uses the number of axles as input parameter.

In [15] the external costs caused by goods vehicle have been determined as CHF 0.038 per km (EUR 0.036) for delivery vans and CHF 0.15 per km (EUR 0.143) for freight trucks. These figures consider health care costs and the noise induced reduction of the property values. Under the assumption that the costs are related to the acoustical energy produced by the traffic it can be concluded that a vehicle with a noise emission differing by ΔL with respect to the average vehicle causes costs $C(\Delta L)$ as given by Eq. 4.

$$C(\Delta L) = C_{\mathsf{ref}} \cdot 10^{0.1\Delta L} \tag{4}$$

where C_{ref} corresponds to the costs as given above for the average delivery van or freight truck. Example: A truck with low noise tires that emit 3 dB(A) less noise compared to the average fleet generates 1.3 dB(A) (Table 3) less total noise on highways. Evaluation of Eq. 4 with ΔL = -1.3 dB(A) yields as costs per vehicle-km CHF 0.11 (EUR 0.106) compared to CHF 0.15 (EUR 0.143) for an average truck.

3. Quieter railway lines

3.1. Railway noise sources

The main sources of noise from the railway system are: rolling noise from the interaction of the wheel and the rail, equipment noise (e.g. fans, engines, cooling systems or compressors), and aerodynamic noise [18]. In general, the spectral contents of railway noise ist slightly shifted to higher frequencies in comparison to road traffic noise. In addition further infrastructure elements cause noise. Among these are the noise from steel bridges, marshalling yards, parked trains, railway stations as well as the noise from squealing trains in tight curves. Between speeds of 40 - 250 km/h rolling noise is most important. Therefore this article focuses on this noise source.

Rolling noise is caused by small irregularities on both the wheel and the rail, causing both to vibrate and emit noise. The most important parameters are the combined roughness of wheel and rail and the decay rate of the rail. The latter describes the vibration reduction of the rail over distance and is strongly influenced by track design. For instance stiffer rail pads increase the decay rate, decreasing noise creation. Further parameters influencing rolling noise creation are the traffic speeds (higher speeds lead to higher noise creation) and the traffic mix (freight trains with cast-iron brake blocks lead to larger wheel roughness which causes more noise).

In rolling noise all elements of the system - rolling stock, track components - interact with one another. If one element of the system is changed, this has an influence on all others. Additionally the optimal combination of track components is different for the various aims within rolling stock or infrastructure and these often contradict on one other. At the same time all legal requirements concerning safety must be fulfilled. It is therefore necessary to optimize the whole system.

Often operational methods are mentioned as possibilities for noise control. These include speed reductions or rerouting. These possibilities are not feasible in most instances because they significantly reduce track capacity along lines where capacity is usually limited as is. A decrease in capacity is not in line with efforts to promote railways as a means of sustainable transport.

3.2. Noise reduction on the side of the vehicle

Wheel roughness - the main parameter influencing noise - depends on the braking system. In systems with cast-iron brake blocks braking is undertaken directly on the wheel, causing irregularities on the wheel running surface. This roughness can be reduced by replacing the cast-iron brake blocks with blocks consisting of composite materials. This leads to a noise reduction between 8 - 10 dB(A) [19] and is probably the most effective means of noise control. A further advantage is that there is a positive effect throughout the network. Currently in use are K- blocks and LL-blocks. Since the braking characteristics of K-blocks are different from cast-iron brake blocks, retrofitting with these blocks requires changing the entire braking system, leading to higher costs. Out of this reason, the LL-brake block was developed, which displays a similar braking characteristic as do cast-iron brake blocks. These blocks were approved in 2014 and future retrofitting is expected to be undertaken with these blocks. Both K- and LL-brake blocks, however, have the disadvantage of causing increased wheel wear leading to increased life cycle costs. The increase in overall freight operating costs are estimated between 2 and 16% [20] as a result of retrofitting.

A further possibility to reduce wheel roughness is the usage of disc brakes, reducing noise in the range of 10 dB(A) when compared to cast-iron brake blocks. The higher expense in comparison to retrofitting with LL-brake blocks and the increase in weight are negative aspects of this possibility. Finally, wheel dampers can be applied. These, however, reduce noise by only a few decibels at best and have therefore not seen a wide application

3.3. Noise reduction on the side of infrastructure

Possibilities on the side of infrastructure include:

Noise barriers: Noise barriers are perhaps the most commonly used method of noise reduction. Depending on the local geometry, they have an effect between 5 and 15 dB. The visual impact is the most important disadvantage in addition to the more difficult access(A) to the track, which may hinder maintenance. Noise barriers can be reduced in height if placed closer to the track, however in many networks this is not possible due to maintenance restrictions as well as safety considerations for workers along the track. In Europe a considerable amount of noise barriers have been built.

Rail grinding: Two types of rail grinding must be addressed [21]: Maintenance grinding and acoustic grinding. 1) Poor maintenance grinding leads to increased corrosion on the rail and may lead to noise increases up to 20 dB(A). Regular maintenance grinding is considered state of the art and is not a noise control method as such. However, it must be noted that if the rail is regularly ground for maintenance, there is also an increase in noise in the first months, which will however decrease again with train passages. 2) Acoustic grinding on the other hand focuses directly on the roughness relevant to noise. This type of grinding is done separately from maintenance grinding. Usually it requires a monitoring of the track roughness in advance, so that the correct locations can be determined. Possibilities are noise measurements of the track with a measurement wagon (the German Schallmesswagen, [22] is an example) or with axle acceleration measurements, which can be combined with a track diagnosis wagon. Some countries, notably Germany with its especially monitored track (besonders berwachtes Gleis [22]), have acoustic grinding programs.

Rail damping: Increasing the track decay rate reduces the noise emitted from the track. This can be done either with rail dampers, products that are applied to the side of the rail, or by changing the track design as such. The effect of rail dampers depends on the track characteristics of the network in question [21]. If the track is stiff, rail dampers have virtually no effect at all, however if the track is softer, noise reductions of up to 3 dB(A) can be achieved. Aside from the cost, rail dampers have the disadvantage of hindering track diagnostics and maintenance. They are also a further track element that must be maintained and replaced. Therefore there are increased efforts to design a damped track. To date the rail pad has been identified as the main element influencing track stiffness and thus noise. The effects of varying rail pad stiffness are similar to rail dampers. Other elements influencing noise are the type of sleeper, the stiffness of under sleeper pads, rail stiffness and the type of fastening. To date, the interactions between these elements are not understood very well yet and further research is needed. One of the main advantages of a noise optimized track would be that no additional components are applied, hence no additional problems with maintenance or diagnostics occur. On the other hand, the aims for noise may contract other infrastructure goals or have a negative effect on vibrations. Therefore it is necessary to optimize the system as a whole. In this regard a project has been started by SBB called Go-Leise (Go-Leise: Gesamtoptimierung, Lärm-, Erschütterungs-, Infrastruktur- und Sicherheitseinflüsse, funded through research funds by the Swiss Government) which aims to optimize the system as a whole. The idea is to find the optimal combinations of track components - possibly relative to local conditions - which reduce noise and at the same time fulfill the requirements of infrastructure LCC, safety and vibrations in the best possible way. In this process, it is possible that individual components such as the rail pad must be improved. The specific aim in a first phase is to gain an overview of the topic, define gaps in knowledge and how they can be filled as well as to determine the optimization methodology in detail.

3.4. Noise reduction near the inhabitant

Noise can also be reduced in the immediate vicinity of the inhabitant, i.e. on the buildings itself. This is usually done with insulated windows or with faade insulation. Noise insulated windows have an effect of 10 - 30 dB(A), which of course is only achieved if the windows are closed. Noise insulated windows are a very common noise mitigation strategy used in most European countries.

3.5. Implementing noise control

Below, a short summary is provided on implementing noise control in Europe, both on an EU and on a national level [23]:

3.5.1. European policy and legislation

The policy of the EU is to promote railway noise reduction while retaining the competitiveness of the railways. Legislative elements at source include the Technical Specification for Interoperability (TSI). The TSI Noise defines limit values for new vehicles. In the newest version, which entered into force on January 1, 2015, slightly reduced limit values are defined in comparison to previous versions and merged conventional and high-speed TSIs. At reception the Environmental Noise Directive (END), which has been in force since 2002 calls for noise mapping and action plans. The WHO (World health Organization) is in the process of updating guidelines and it is expected that the EU Commission will be guided by these in the future. The directive 2012/34/EU foresees an optional introduction of noise differentiated track access charges (NDTAC). The Connecting Europe Facility (CEF) allows for the possibility to co-fund retrofitting of freight wagons with 20% of the eligible costs.

An impact assessment on "Effective reduction of noise generated by railway freight wagons in use in the European Union" [24] has been completed and will form the basis for a mid- and long-term strategy for rail noise abatement was communicated in a "Staff Working Document" [25] in December of 2015. The working document proposes a policy mix that includes:

- The harmonization of noise-charging principles.
- A recommendation on financial support to retrofit freight wagons.
- Development of noise-related standards of railway tracks.
- The gradual applicability of TSI-Noise limits to existing freight wagons that serve international routes, followed by an obligation of all freight wagons circulating in the EU to be TSI-Noise compliant.

3.5.2. National policy and legislation

In addition to the European policy, individual countries have policies and legislation of their own. Most countries have programs to build noise barriers and some plan to retrofit wagons with composite brake blocks. Here are some examples of countries along the Rhine Alpine Corridor [26].

The Netherlands: Noise reduction is undertaken by local infrastructure measures, by a scheme maximizing the planned level of noise for an identified area as well as measures at and around infrastructure and buildings. In terms of measures at source, the Netherlands have a scheme of noise differentiated track access charges (NDTAC, in which silent freight wagons pay lower track access charges) with a four year time limit which will be adapted to meet the requirements of the Implementing Act NDTAC 2015/429/EU by 2016.

Belgium: Currently there is no funding for retrofitting nor are there any legislative actions. However a study was undertaken as a basis for a political decision in 2016. Measures under discussion are bans (total, night, geographical zones), NDTAC schemes, subsidies for retrofitting or renewal or no action at all.

Germany: Germany aims to halve railway noise by 2020. To this end the retrofitting progress will be evaluated in 2016 and if not satisfactory, a ban on noisy wagons will be effected as of 2020. A NDTAC system was introduced in 2012 scheduled to run for 8 years. In addition grants for retrofitting are given to wagon owners. As of June 2015 funding applications for more than 160'000 wagons were received. DB Schenker Rail started retrofitting in 2014 and about 10'000 wagons have been retrofitted since then. Also, until 2020 DB Schenker Rail will have about 10'000 new wagons with K-brakes in use. In addition noise barriers and noise insulated windows are being installed as part of a government funded program and certain tracks are acoustically grinded.

Switzerland: In a first step until 2015 all Swiss wagons were retrofitted with composite brake blocks, some 250 km of noise barriers were constructed and insulated windows installed. As an additional incentive, NDTAC were introduced. Retrofitting and noise barriers protected about two thirds of the noise affected population. In a second step the NDTAC were doubled, a ban of noisy wagons will be introduced by 2020 and financing made available for measures on the track.

Italy: The Italian infrastructure operator is obliged to spend at least 7%

of the maintenance budget on noise control measures. In terms of measures at source, no incentive or financing programs have been introduced to date.

3.5.3. Noise Control Strategy of the Railways

In response to legislation and considering the options for noise control, the railways in general have adopted the following strategy [27]:

- The railway sector promotes retrofitting of the cast-iron brake blocks of existing freight wagons with composite brake blocks. However, remaining financial, technical and administrative concerns must be addressed. In particular the competitiveness of the railways must not be endangered. In addition all new wagons conform to the TSI and are thus silent.
- The railways construct noise barriers where the noise effects form retrofitting of existing wagons with composite brake blocks are insufficient. This complementary measure must meet cost-benefit criteria however.
- In certain hot spots further measures on the infrastructure (e.g. damping of the track) can be tested if they fulfil satisfactory cost-benefit criteria.

4. Discussion and Conclusions

Road traffic noise is composed of rolling noise and propulsion noise. In modern passenger cars rolling noise dominates over propulsion noise for speeds above 30 km/h, for trucks that speed threshold is significantly higher, according to CNOSSOS at around 75 km/h. While low noise tires exhibit a significant noise abatement potential for passenger cars already at urban speed regimes, heavy vehicles substantially benefit from low noise tires at highway speeds only. However as heavy vehicles mostly drive on highways, low noise tires can contribute to substantial noise reduction.

A recent compilation of international experiences has revealed that low-noise pavements can constitute an effective noise abatement measure at the source.

Low-noise pavements are economically very attractive, especially if they supersede the installation of a noise barrier to attain the desired noise protection. A major challenge remains to maintain the noise reduction over a larger period of time. An alternative approach is to change the paradigm that the life span of a pavement should amount to 20 or 25 years. Depending on the situation it may turn out to be advantageous to replace a low noise pavement more often and to profit from a distinct noise reduction in return.
While society decides on the installation of low-noise pavements, individuals as owners of the vehicles are responsible for the utilization of low-noise tires. However, society has the possibility to motivate low-noise tires by consideration of the tire type in a heavy duty vehicle fee. With help of a model that allocates noise to costs, the effect of a low noise tire can be expressed as a money equivalent and used as a bonus in the fee. Though, several recent studies [28] have shown that there is a significant uncertainty in the applicability of tire label values in situations with usual operational road surfaces. Additional research is needed to identify the range of application of the tire label information. If it turns out that the gap between the tire label values and tire noise measurements on typical road surfaces is too big, a reformulation of the corresponding standard and/or an alternative method to collect tire data should be considered.

Railway noise is dominated by rolling noise that develops from the interaction of the wheel and the rail. The most important factor that influences rolling noise is the combined roughness of wheel and rail. Wheel roughness strongly depends on the breaking system. In freight waggons retrofitting of cast-iron break blocks with blocks consisting of composite materials or the installation of disc brakes is a very effective measure to lower noise emission. By the introduction of track access charges that differ according to the breaking system, the owner of the infrastructure can stimulate the retrofitting process. A big advantage of measures taken at the vehicle is the fact that the effect is present along the complete railroad network. As noise emission depends on the combined roughness of wheel and rail, a smooth wheel is most efficient on smooth rails.

On side of the infrastructure, the erection of noise barriers, acoustically optimized rail grinding or rail damping are measures to further lower noise emission of railway lines. As adjustments in one domain impact aspects in other domains, it is necessary to optimize the system as a whole. Additional research and the development of numerical simulation tools is needed for an efficient and goal-oriented optimization of the wheel rail system.

As a consolidated overview, Table 4 summarizes the discussed noise abatement strategies both for road and rail.

measure	noise reduction potential	remarks
low noise truck tires	2 dB(A)	speeds above 80 km/h
low noise passenger car tires	3 dB(A)	speeds above 50 km/h
low noise pavements	up to 10 dB(A)	passenger cars above 80 km/h
rail vehicle braking system	up to 10 dB(A)	compared to cast-iron blocks
rail vehicle wheel dampers	3 dB(A)	not widely used
rail grinding	3 dB(A)	in combination with smooth wheels
rail damping	0..3 dB(A)	depends on track stiffness
noise barriers	5..15 dB(A)	for road and rail

Table 4: Compilation of the discussed noise abatement measures for road and rail.

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