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Impact assessment of a railway noise in an alpine valley

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Much of the existing European legislation on railway noise impact assessment refers to indicators based on long term weighted averages of acoustic intensities (L_{dn}, L_{den}, L_{eq}). However, several studies have pointed out that noise event indicators are more appropriate in order to evaluate annoyance due to intermittent noise sources, such as those due to rail traffic. The computation of these short-term averaged indicators (L_{max}, SEL) requires the estimation of the instantaneous sound level in the surrounding areas, over a region of several square kilometers. We have developed an analytical model, named TR-Noise, for the outdoor propagation of rail traffic generated noise. TR-Noise adopts a quasi-steady description of outdoor noise propagation to compute cartography of instantaneous sound level and therefore short-term averaged indicators. The noise sources are modelled as a weighted sum of monopole and dipole moving at uniform velocity along a rail track. The model of ambient noise propagation is based on the ISO/DIS 9613-2 International Standards and takes into account different mechanisms of sound attenuation in the ambient. The model has been used to study the impact assessment of a new railway in a dense populated alpine valley. Firstly, the model was calibrated by means of a field measurement campaign. Sound level measurements performed close to the rail track have been used to estimate the intensity of the source strength related to different kind of trains. Measurements at larger distances from the rail track allowed us to evaluate the performance of the model and to define the influence of different factors contributing to sound attenuation. Results show that the model is a reliable tool to simulate sound level cartographies due future scenarios of rail traffic and evaluate their impact on the population.

1 Introduction

In recent years new high capacity railway tracks have been planned or constructed to promote rail freight in Europe. Due to the high frequency of train transit, which is not necessarily interrupted during the night, these lines have a significant socio-environmental impact on the population living in the surrounding areas. The impact is greater within alpine valleys, whose width is smaller than the height of valley walls, within which there are worse conditions for noise attenuation.

Nowadays to asses the impact of outdoor noise pollution much part of the existing European legislation refers to indicators based on long term weighted averages of acoustic intensities, referred to as L_{dn}, L_{den}, L_{eq}. These are usually evaluated following the ISO/DIS 9613-2 International Standards, which provide a model to compute these indicators taking account reflections by obstacles, the influence of atmospheric conditions (thermal stratification and wind shear), sound attenuation with distance from the source, attenuation due to vegetation and ground effects.

This impact assessment methodology presents two main problems. The first one concerns reliability of long term weighted average of acoustic intensities as appropriate indicators to quantify annoyance due to intermittent noise sources. The second one is related to the outdoor propagation model provided by the ISO/DIS 9613-2 which is not well adapted to noise events in sites with complex topographies. Considering the impact of a railway in a densly populated alpine valley both factors are critical.

The aim of this paper is to define an appropriate impact assessment methodology for railways noise in an alpine environment. To that purpose in §2 we summarise the particular aspect of sound propagation in this environment and the basic existing literature on the impact of intermittent noise events on human health. The methodology is presented in §3 and is based on an analytical model for time-dependent noise propagation. An example of application is provided in §4. Conclusions are drawn in §5.

2 Railways noise in alpine valleys

2.1 Limitations of the ISO/DIS 9613-2

The ISO/DIS 9613-2 International standard is based on simple analytical models for outdoor sound propagation in order to predict the levels of environmental noise which is valid for a variety of situations given that the sound propagation occurs over almost 'flat'' terrain and in presence of a 'light' wind (≤ 5 m s^{-1}). It has two main limitations that concern the computation of sound attenuation due to the ground and the influence of inhomogeneities of the dynamic and thermodynamic conditions of the lower atmosphere.

The estimate of the sound attenuation due to the ground mainly takes into account the destructive wave interference of direct and reflected acoustic rays. This effect can be significant over flat terrain and for slight curvature of acoustic rays and can produce important attenuation of sound for receptors located at mid distances from the source (few hundreds of meters) and small distances from the ground. Conversely, when the ground morphology is characterised by a high concavity we can reasonably assume that these mechanisms for sound attenuation are almost ineffective.

The estimate of the influence atmospheric conditions takes into account the effect of the curvature of acoustic rays induced by inhomogeneities in the atmospheric conditions. Nevertheless the model is valid for slight curvatures and therefore fails in case of significant wind shear or to a strong thermal stratification. These conditions actually characterise the micro-meteorological conditions in valley where thermal inversion close to the ground and episode of foehn frequently occur [1].

For these reasons the ISO/DIS 9613-2 is not well adapted to model outdoor noise propagation in a deep valley and has therefore to be handled with care when applied to this environment.

2.2 Noise intermittency and annoyance

As already mentioned in the introduction almost all the existing European legislations on transport generated noise are based on long term weighted averages of acoustic intensities, such as L_{dn}, L_{den}, L_{eq}. An exception is given by the Swedish legislation that prescribes also a limit of maximal level of acoustic intensities, referred to as L_{max}. However, from the 1980s, several studies pointed out that these indicators are not reliable in order to evaluate the annoyance induced by intermittent and impulsive sources of noise, such as trains and aircraft. A complete review of these studies can be found in the book by Kalivoda and Steiner [2]. As an example we refer here to the work of Taylor [3] and Hall [4] who showed the slight correlation between perceived annoyance and L_{eq} when considering aircraft noise compared to other kind of noises. There are in particular two main aspects that characterise railway or aircraft noise events. One is the rapid increase of sound level and the other the gap between the maximal level and background noise levels. It is well known that both factors contribute in worsen the perception of noise [5]. For these reason some author suggest to replace L_{eq} with L_{max} in order to characterise these noise events [6,7]. Facing the same problem, years before Robinson [8] proposed to quantify the level of noise pollution by means of a mixed indicator, referred to as L_{NP}, obtained by a linear combination of the two first order moments of the statistical distribution of time dependent sound levels:

$$L_{NP} = L_{eq} + k\sigma$$

where σ is the standard deviation and k an empirical constant equal to 2.56.

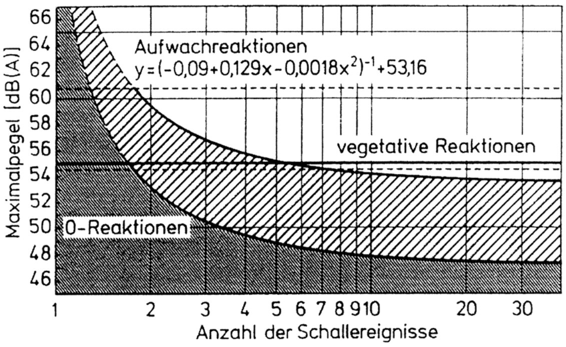

Figure 1: Awakening threshold as a function of the number (x-axis) and the maximal acoustic level (y-axis) of noise episodes [12] .

Nevertheless it is worth noting that the impact of these noise events on the population is considerably different during night periods. Due to the undisputed restorative function of sleep, its disturbance is regarded as the most deleterious effect of intermittent and impulsive noise [9,10,11]. Experimental work [12,13] has shown that a relatively low threshold, between 52 dB(A) and 60 dB(A), awakens the more sensitive part of the population. Furthermore, these studies showed that this threshold is reduced for enhanced gap between the background level and L_{max}, that the percentage of the people awakened by a noise event increases with increasing L_{max} and that the time required to fall asleep after these events increases with increasing L_{max}. In order to quantify the disturbances of intermittent noises on sleep, Griefhan [14] reviewed the results of the existing body of literature and empirically defined the dependence of the awakening threshold on the number of noise events N and L_{max}. The result is shown in figure 1, where the x-axis refers to the number of events N (in a logarithmic scale) and the y- axis refers to L_{max}. The darkest part of the diagram concerns conditions that do not imply any sleep disturbance, whereas the shaded area refer to vegetative reactions. The upper limit of this region defines the L_{max} corresponding to the awakening threshold, which rapidly decreases with increasing number of events N. The diagram can be used to evaluate the level L_{max} that induce awakening as a function of the number of events, which is expressed as

$$L_{max} = \frac{1}{-0.018N^2 + 0.129N - 0.09} + 53,16 \qquad (1)$$

In our opinion an impact assessment of a railway which is planned for daily and nocturnal transits has primarily to estimate the effect of intermittent noise events during the night. To that purpose the diagram in figure 1 provides a useful tool in order to quantify the impact of railway noise on the population in the surrounding areas relating it to the number and the maximal level of events.

3 A methodology for impact assessment

The need for a new methodology for impact assessment is driven by environmental issues related to new high-capacity railway tracks in the Alps. These have been planned to promote freight transport and schedule a high frequency of transits during both day and nighttime. It was immediately clear that these lines would have a high environmental impact when passing through dense populated alpine valleys and that the adoption of indicators based on long term weighted averages of acoustic intensities (L_{dn}, L_{den}, L_{eq}) would have led to underestimate their impact. In these valleys, as the Susa valley (§4), a large amount of the population is distributed along the mountain slopes and is therefore particularly exposed to ambient noise pollution generated by train traveling at the bottom of the valley. Furthermore, it is well known that in these conditions usual devices adopted to reduce the impact such as noise barrier turn out to be ineffective. Therefore in order to define the environmental limit of these lines it is essential to evaluate accurately the frequency of the noise events and the associated acoustic levels in the surrounding areas.

The methodology we adopted is based on calculations performed with a code, named TR-Noise, to estimate acoustic intensities. The code, which is presented in §3.1, was conceived to model time-dependent acoustic intensities due to moving noise sources. The code is based on simplifying assumptions and requires an accurate calibration by means of in situ measurements (§3.2). Once calibrated it can be used to simulate sound level cartographies due to future scenarios of rail traffic and evaluate their impact on the population.

3.1 Modelling

TR-Noise adopts a quasi-steady description of outdoor noise propagation to compute cartography of instantaneous sound level. The noise sources are modelled as a weighted sum of monopole and dipole moving at uniform velocity along a rail track. The main difference between TR-Noise and other codes based on ISO/DIS 9613-2 (e.g. SoundPlan, Mithra) that compute directly long term weighted averages of acoustic intensities (L_{dn}, L_{den}, L_{eq}) is that TR-Noise TR-Noise computes time-dependent acoustic intensities. TR-Noise can therefore compute the increase in sound level while the train is approaching and the subsequent reduction while the train moves away. In this way we can infer several information of each single noise event, including the duration of the events, their maximal level, the increase ratio of instantaneous acoustic levels and of course the Single Event Level (SEL). These represent essential information in order to estimate annoyance during the night time (§2.2).

As an example we show some results provided by TR-Noise. In figure 2 we show the temporal evolution of a acoustic intensities registered at a fixed point whereas in figure 3 we show the field of acoustic intensities produced by a train moving along the railway track.

The model of ambient noise propagation is based on the ISO/DIS 9613-2 International Standards and takes into account different mechanisms of sound attenuation in the ambient. These include geometrical divergence and atmospheric absorption for different octave band. However TR-Noise does not take into account the reflections due to the presence of obstacles neither the effect of sound attenuation due to the ground. The are several reasons for this choice. As discussed in §2.1 the complexity of the topography within an alpine valley makes inappropriate the ground attenuation model provided by the ISO/DIS 9613-2. A more accurate estimate of this effect, and of that of reflections, would require the tracing of a large number of acoustic rays. This should be performed over a domain of several square kilometers and for each time step of the simulation therefore requiring a significant computational effort. Nevertheless we can reasonably assume the attenuation of sound due to ground effects as almost negligible for a large part of the receptors located in elevated position with respect to the railway track. We therefore chose to neglect these effect in order to keep our model as simple of possible. It is worth noting that the hypothesis of negligible attenuation due to the ground can not be verified 'a priori' and need to be verified for each single case by an accurate comparison between numerical results and in-situ experiments.

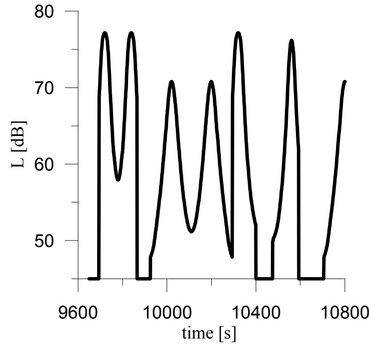

Figure 2: Temporal evolution of sound level L computed by TR-Noise at a fixed position.

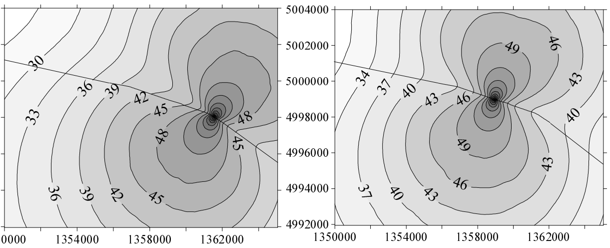

Figure 3: Isolines of acoustic levels [dB(A)] computed by TR-Noise; x-axis and y-axis refer to UTM coordinate system.

Summarising, we do not expect TR-Noise to provide reliable results at small distances from the source in case of sound propagating over flat terrain or characterised by a large number of obstacles. Conversely TR-Noise can give reliable results when ground effects play a negligible role, i.e. for mid or large distances from the sources and provided that sound propagation occurs in an open acoustic field.

3.2 Calibration of the model

The experimental measurements are necessary to calibrate the model and verify the reliability of its results. They allow us to infer two main features:

- the accuracy of the hypotheses adopted by the model, especially concerning the effect of the ground on noise propagation.

- the specific acoustic power (per unit length) emitted by different trains;

The first aim is to estimate the sound attenuation with the distance from the source in different locations. Generally speaking the attenuation depends on three factors: geometrical divergence, atmospheric absorption and ground effects. As mentioned in the previous paragraphs, the latter depends on the morphology of the terrain and on the presence of obstacles and is neglected by TR-Noise in computing outdoor sound propagation (§3.1). A comparison between experimental and numerical calculation is then necessary to estimate systematic errors due to the adoption of this simplifying hypothesis. Only after this comparison we will be able to use the results of the simulations with higher confidence and define the areas where the simulations provide reliable results.

The generic characteristic of acoustic power per unit length emitted for different kind of train as a function of their velocity are available in the literature. However to remove further sources of error in our numerical results we preferred to estimate them directly. These could be inferred by sound level measurements performed close ($\sim 10m$) to the rail track. The parameter used to calibrate the model is the SEL, which is a measure of the acoustic energy emitted by the noise source and can be directly computed by the acoustic signals registered close to the source.

4 The case of the Susa Valley

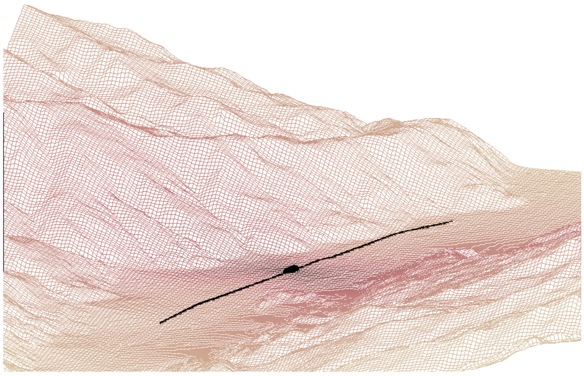

Figure 4: Orography of the Susa Valley and railway track.

This methodology of impact assessment has been so far applied to different cases [15,16]. Here we report results obtained in the impact assessment of a railway in northern Italy, namely in the Susa Valley. The Susa Valley extends over approximately 50 km in an east-west direction from the French border to the outskirts of Turin. Here we are mainly concerned with its eastern part, where a new high-capacity railway track has been planned. This part of the valley is characterised by a width of about 1 Km and is bordered by mountains which can exceed 3000 m high (figure 4). Given the reduced distances to the town of Turin (few tens of kilometers) this part of the valley has been progressively occupied by an increasing urbanisation which implies today a high density of population (about 65.000 habitants over approximately 80 square kilometers). The high concavity of the ground and the high density of the population make this area very sensible to noise pollution. To asses the environmental impact of the new railway we have calibrated TR-Noise with a series of on site measurements performed on train traveling on the existing line. Moving from these results we could then estimate the impact of the new line considering the scheduled transit frequency for the future.

We emphasise that the aim of this section is not to give the details of the results of the impact assessment of the planned new railway [16], whereas to show the reliability of the methodology proposed in §3 by comparing on site measurements close to the existing railway and numerical simulations performed with TR-Noise.

4.1 Measurements campaign

The measurement campaign has been performed between 21 pm of June 6^{th} 2001 and 2 am of the following day. Measurements during evening and night time allowed us to capture signals with minimal ambient noise disturbances. It is worth noting that some of the measurements occurred when strong wind gusts took place.

Noise signals were recorded with a class I microphone, as prescribed by the standards EN 60651/1994 and EN 60804/1994. The microphone was accurately calibrated before and after each series of measurements. We performed the noise measurements in four different locations, referred to as $PM1$-$PM4$, at increasing distance of the railway track. All receptors are located to the north of the track along a line perpendicular to it. The relative elevation and distance of the receptors from the track is given in table 1. 18 different noise signals were acquired. For each event we could also register the length of the train, the type of train and its velocity.

Receptor	Δz [m]	d [m]
$PM1$	-	11
$PM2$	-	215
$PM3$	13	643
$PM4$	68	750

Table 1: Elevation Δz and distance d of the receptors with respect to the railway track.

4.1.1 Noise Source strength

The closest receptor ($PM1$) was used to infer the acoustic power at the source for different type of train. The parameter used to calibrate the model defining the acoustic power per unit length emitted by the transit of a train is the SEL registered at $PM1$. As shown in figure 5-a we varied the acoustic power per unit length in order to have a perfect accordance between measured and calculated SEL for different events. This constraint does not imply same maximal acoustic levels L_{max} at the same receptors (figure 5-b).

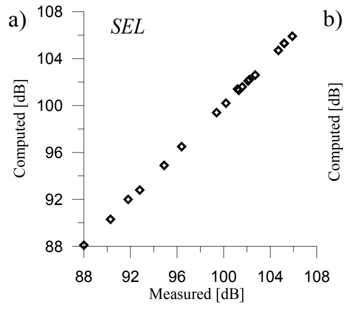

Figure 5: Calibration of the model on signal acquired in $PM1$. a) SEL; b) L_{max}.

We could observe that the speed of the train increased gradually during the night. However an increased speed did not correspond necessarily to enhanced acoustic power per unit length since this depends also on the weight of the trucks and their mechanical characteristics.

4.2 Comparison between experimental and numerical results and discussion

Even if some of the measurements were disturbed by occasional noise events (barking dogs, doors or rolling shutters...) which produced spurious peaks in the signals, the ensemble of the data allowed us to infer the main aspects characterising sound propagation in the lowest part of the valley.

	$PM1$	$PM2$	$PM3$	$PM4$
Meas.	101.6	81.2	82.2	75.8
Comp.	101.6	87.9	81.2	79.9

Table 2: Measured and computed $< SEL >$ [dB(A)].

We report here results concerning SEL and L_{max} computed for each event. A comparison between numerical and experimental results is shown in figures 6-7-8 whereas in table 2 the ensemble averaged values of these two indicators, referred to as $< SEL >$ and $< L_{max} >$, are given. We observe that for increasing distances from the track measured and calculated values of SEL and L_{max} decay differently and that the behaviour of these two parameters is not the same in the three receptors considered.

	$PM1$	$PM2$	$PM3$	$PM4$
Meas.	90.8	67.5	69.6	59.1
Comp.	89.9	74.7	66.1	63.4

Table 3: Measured and computed $< L_{max} >$ [dB(A)].

In $PM2$ the measured values are almost always 7 dB(A) smaller than those computed by TR-Noise. Given the reduced distance from the track this attenuation can not be explained by meteorological factors. Conversely, since this receptor is located at the same altitude of the railway track, we can reasonably assume that this systematic difference relies on mechanisms of destructive wave interference due to reflections on the ground, whose influence is not taken into account in our computations. However it is worth noting that the measured attenuated sound level are about 2 or 3 dB(A) higher than those predicted assuming the ground attenuation model of the ISO/DIS 9613-2.

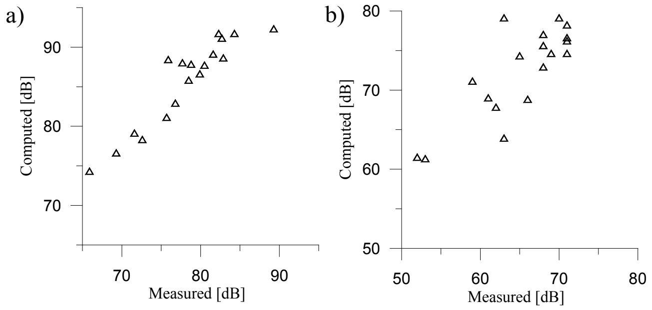

Figure 6: Comparison between measurements and simulations in $PM2$. a) SEL; b) L_{max}.

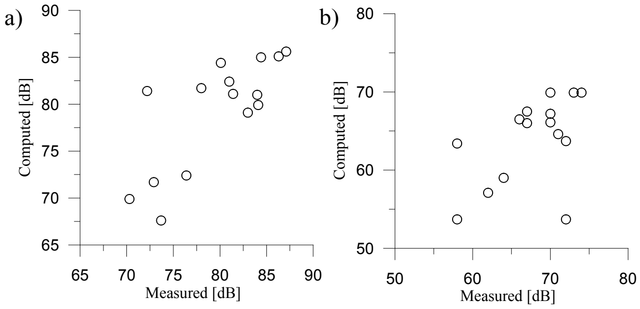

Figure 7: Comparison between measurements and simulations in $PM3$. a) SEL; b) L_{max}.

Results in PM3 show the best agreement between measurements and simulations (figure 7). The measured $< SEL >$ is about 1 dB(A) higher than that calculated by TR-Noise. This can be explained by the position of the microphone, which was placed at a post close (2 m) to a building wall where sound reflections could take place. The accordance between numerical and simulated sound levels implies that a difference in height of about 13 m on a distance of 643 m is enough to cancel the attenuation effect produced by the ground and observed in $PM2$. This is mainly due to the topography of the ground between the source and the track that is characterised by an abrupt increase in height close to $PM2$. This produces locally a high concavity of the terrain which makes the sound propagation very similar to that occurring in an unbounded space. This result clearly shows that in this kind of environment the effect of attenuation of sound due to the ground is almost negligible, at least for all those receptors which are located few tens of meters above the track.

Given the location of $PM4$ we would have expected results similar to those registered in $PM3$. However the results in figure 8 show a higher scatter of the data, whereas table 2 show that in average the values of $< SEL >$ and $< L_{max} >$ are larger of about 4 dB(A) than those measured. This attenuation is significantly smaller than that registered in $PM2$ and can not be reasonably attributed to the ground. We explain the differences observed in $PM4$ to meteorological factors, in particular to the presence of sudden gusts of wind. Given the larger distance of $PM4$ from the track (750

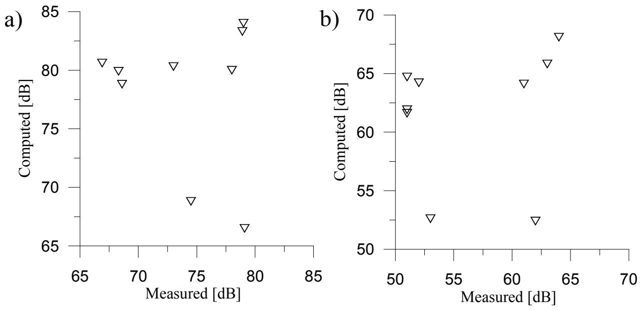

Figure 8: Comparison between measurements and simulations in $PM4$. a) SEL; b) L_{max}.

m) we can assume that the influence of these effect could become relevant and induce an attenuation larger than that observed in $PM3$, even if this latter receptor is less elevated compared to the track. To verify this hypothesis we recomputed the averaged indicators $< SEL >$ and $< L_{max} >$ excluding the values corresponding to noise events taking place during wind gusts. The results are given in table 3, which show a much better accordance between measured and computed data for both $PM3$ and $PM4$. This is true especially in case for $PM4$ whose corresponding averaged values are significantly reduced when compared to those given in table 2, obtained considering all noise events. This feature confirms our assumptions on the influence of the meteorological effects.

	PM-3		PM-4	
	$< SEL >$	$< L_{max} >$	$< SEL >$	$< L_{max} >$
Meas.	83.0	70.0	76.8	60.1
Comp.	82.5	66.8	79.5	62.8

Table 4: Values of $< SEL >$ and $< L_{max} >$ computed excluding noise events disturbed by wind gusts.

Summarising, the difference between experimental and numerical results can be qualitatively interpreted in all receptors. Quantitatively, they show a remarkable agreement in $PM3$. In particular, this latter result shows that a difference in height of about ten meters implies almost negligible sound attenuation due to the ground. We stress here the importance of this result and its implication on noise pollution in an alpine environment as the Susa Valley, where most of the houses are located above the railway mine and are therefore extremely exposed to noise episodes.

5 Conclusion

We have discussed the problems related to the impact assessment of railway noise in a densely populated Alpine Valley. These are mainly related to two critical factors. Firstly, the intermittency of the source of noise, which can be the cause of severe annoyance, especially during night time. Secondly the negligible attenuation of sound over a concave terrain, which implies high level of exposure to noise pollution for all people living along the slope of the mountains. In order to take into account these aspects we have developed a numerical code for impact assessment in this environment. By a comparison with in-situ measurements we show that TR-noise can be a reliable tool for predicting sound level in alpine environment and therefore assessing the impact of railway tracks.

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