inter.noise HAMBURG 2016

# Parameter study on IR, a metric reflecting short-term temporal variations of transportation noise exposure

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## ABSTRACT

It has been hypothesized that noise induced health effects not only depend on acoustic exposure metrics reflecting the average energetic dose but also on other aspects of noise exposure such as the level variations over time. Such a new acoustic descriptor called Intermittency Ratio IR has been introduced within the framework of the SiRENE project, a study which investigates transportation noise effects in the Swiss population. IR reflects the eventfulness of an exposure situation and is intended to add an additional dimension to the well-established Leq and related measures. In this paper the method to estimate IR for traffic noise sources based on calculations is presented. In order to predict IR for road traffic noise, several assumptions on traffic flow and composition have to be made. A validation of these settings and a parameter optimization are performed. Additionally a parameter study is included to show the dependency of IR on distance, traffic volume and the percentage of heavy traffic.

Keywords: Noise exposure, Intermittent noise, Noise metric, Modelling, Noise mapping
I-INCE Classification of Subjects Number: 68.3

## 1. INTRODUCTION

Transportation noise, largely from road, railway and aircraft traffic, is one of the most widespread sources of environmental stress and discomfort in daily life. Health effects of noise may emerge directly via autonomous stress reactions to the physical exposure or indirectly via negative affective states, e.g. annoyance.

Typically epidemiological studies as well as many annoyance surveys consider noise exposure as equivalent continuous levels over longer time periods (e.g. Ldn, Lden, Lnight or Lday (1, 2)). These energy-based exposure measures were accepted to be the most reliable acoustic predictors in the last decades. However their explanatory power regarding annoyance or disturbance effects is often limited and it is questioned whether information on the temporal structure of sound, especially the presence of clearly noticeable single events (3) or calm periods in between (4) might provide additional explanatory power.

Importantly, humans perceive, evaluate and react to environmental sounds not only during daytime, but also while asleep. And in this state an overall sound intensity dose seems even less appropriate to describe acute and short-term effects on sleep such as conscious and unconscious awakenings, shifts to lighter sleep stages, cortical and cardiovascular arousals (increases of heart rate and blood pressure), and body movements (5-9). The probabilities of such reactions are more clearly correlated with acoustic characteristics of noise events, especially with the number of events, the maximum sound

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pressure level and the slope of rise of the level (10, 11).

Hence it can be concluded that for health effect studies, which integrally evaluate the effects of noise during day and night, solely energy-based exposure measures may not be sufficient and should be complemented by additional measures that describe the temporal structure of the noise exposure.

In the last decades there have in fact been several proposals to add time related variables to replace or supplement the Leq. A discussion of alternatives or amendments to the Leq can be found in (12) and (13). Common approaches are the introduction of thresholds and the counting of the number and duration of events above the threshold (e.g. the Noise and Number Index NNI) or the use of level statistics. These are for example the basis of derived quantities such as the Traffic Noise Index (14), the Noise Pollution Level (15), or the Common Noise Index CNI (16). However these metrics have not yet reached a broader application for regulatory purposes either because they highly correlate with the Leq or for reasons of complexity to be implemented in or combined with common calculation models.

The present work was stimulated by the demands of the SiRENE study (17, 18) which investigates transportation noise effects in the Swiss population. One goal of the project is to elucidate the effect of source intermittence on cardiovascular morbidity and mortality in two large-scale epidemiological studies (the SAPALDIA cohort and the SNC study). With the goal of providing nation-wide exposure data, a new metric called Intermittency Ratio ($IR$) was introduced (19). $IR$ intends to yield an integral description of the eventfulness (or: "intermittency") of noise exposure situations, taking into account both number and magnitude of noise events during a certain time period. $IR$ is defined in a way which allows an estimate based on generally available information on traffic and source-receiver geometry. In section 2 the concept of $IR$ and the calculation method are briefly introduced (for details see (19)). In order to predict $IR$ for road traffic noise, several assumptions on traffic flow and composition have to be made. A validation of these settings and a parameter optimization are performed in section 3. Additionally a parameter study is included in section 0 to show the dependency of $IR$ on distance, traffic volume, percentage of heavy traffic and travelling speed.

## 2. INTERMITTENCY RATIO (IR)

### 2.1 Basic principle

Highly intermittent traffic noise exposure situations consist of subsequent pass-bys of vehicles (cars, aircraft, trains...) which acoustically stand out from the background (noise) by a certain degree. We define such parts of the level-time course as "noise events". For an integral characterization of the "eventfulness" of an exposure situation over a longer period of time we introduce the event-based sound pressure level $L_{\mathrm{eq,T,Events}}$, which accounts for all sound energy contributions that exceed a given threshold. This event-based sound pressure level $L_{\mathrm{eq,T,Events}}$ can now be compared to the overall sound pressure level $L_{\mathrm{eq,T,tot}}$, i.e., the equivalent continuous sound pressure level of all sound sources together. The Intermittency Ratio $IR$ is defined as the ratio of the event-based sound energy to the overall sound energy.

$$IR \equiv \frac{10^{0.1 L_{eq,T,Events}}}{10^{0.1 L_{eq,T,tot}}} \cdot 100 = 10^{0.1\left(L_{\mathrm{eq,T,Events}} - L_{\mathrm{eq,T,tot}}\right)} \cdot 100\ [\%] \tag{1}$$

A single pass-by only contributes to $L_{\mathrm{eq,T,Events}}$ if its level exceeds a given threshold $K$.

$$K \equiv L_{\mathrm{eq,T,tot}} + C\ [\mathrm{dB}] \tag{2}$$

This threshold $K$ is defined relative to the long-term average of the overall sound pressure level $L_{\mathrm{eq,T,tot}}$ and an offset $C$. The latter is the only free parameter within the definition of $IR$ and has been set based on numerical simulations of various traffic situations to $C$ = 3 dB.

By definition, $IR$ only takes values between 0 and 100% (including 0% and 100%). An $IR$ of higher than 50% means that more than half of the sound dose is caused by "distinct" pass-by events. In situations with only events that clearly emerge from background noise (e.g. a receiver point close by a railway track), $IR$ yields values close to 100%.

### 2.2 Estimation of the Intermittency Ratio by calculation

The general idea is to extend the exposure assessment metrics of existing noise mapping tools with $IR$. Therefore the calculation of $IR$ uses information that common engineering tools rely on for their emission and propagation calculation. An estimation of IR by calculation is performed in six steps:

1) The maximum level of a single pass-by in a given source-receiver geometry $L_{\mathrm{Fmax}}$ is estimated based on the equivalent continuous sound pressure level of a single pass-by $L_{\mathrm{eq,T,single}}$, the vehicle speed, the shortest distance and the source path aspect angle. $L_{\mathrm{eq,T,single}}$ is taken from the underlying noise calculation model and therefore already includes specific properties of the propagation situation such as barrier and ground effects.
2) For each vehicle category a distribution of maximum levels $\mathrm{h}(L_{\mathrm{Fmax}})$ is derived by adding a source level standard deviation $\sigma_0$. It is assumed that the maximum levels of single pass-bys are normally distributed. For road traffic an additional variation in level $\sigma_{\mathrm{OL}}$ is introduced to account for the temporary overlap of single pass-by events, which will be discussed in detail in section 3.
3) Based on the distribution of maximum levels the number of events N that exceed the threshold *K* is determined.
4) Additionally a weighting function $w(L_{\mathrm{Fmax}})$ is introduced that considers the truncation effect due to the finite line source length to ensure that for a given event only the intensity above the threshold K is integrated.
5) The event-based sound pressure level $L_{\mathrm{eq,T,Events}}$ is then estimated as shown in Equation (3) as an integral over all pass-by events of the assessment period. Thereby $\Delta L = L_{\mathrm{Fmax}} - L_{\mathrm{eq,T,single}}$ [dB].
6) Finally an estimate of *IR* is derived according to the definition in Equation (1).

$$L_{\mathrm{eq,T,Events}} = 10 \cdot \log_{10}\left(N \cdot \int_K^{\infty} h\,(L_{\mathrm{Fmax}}) w(L_{\mathrm{Fmax}}) 10^{0.1 L_{\mathrm{Fmax}}} dL_{\mathrm{Fmax}}\right) - \Delta L \text{ [dB]} \qquad (3)$$

## 3. PARAMETER SETTING TO ESTIMATE THE LEVEL DISTRIBUTION

The applied vehicle categorization and the associated standard deviations $\sigma_0$, which reflect the variation of the sound power level within a vehicle category, have a major influence on the distribution of maximum levels and hence on the resulting IR. For the current application of *IR* within the project *SiRENE* it was concluded that a representative standard deviation $\sigma_0 = 2$ dB can be used for all vehicle categories such as passenger cars, heavy and light trucks, different types of trains and aircraft and that the assumption of a normal distribution was valid.

The standard deviation $\sigma_0$ already accounts for minor variations in travelling speed. In case of significant speed variations it is recommended to subdivide the categories and to model them individually.

Normally, single pass-by events of trains and aircraft are separated in time and therefore a temporal overlapping of events can be neglected. This however does not hold for road traffic noise where typically the number of vehicles per time is much greater and traffic often flows bidirectional on several lanes.

The influence of the overlap effect on *IR* in the case of road traffic noise was therefore investigated in (19) by numerical simulations. Simulation data of periodically and stochastically distributed pass-by times were used as the two marginal cases. It could be shown that IR between 0 and 0.5 in particular are affected. It was found that this effect could be approximated by an artificial increase of the standard deviation of the level by

$$\sigma = \sqrt{\sigma_0^2 + \sigma_{\mathrm{OL}}^2} \qquad (4)$$

with $\sigma_0$ being the single source standard deviation and $\sigma_{\mathrm{OL}}$ an additional standard deviation for the temporal overlap. At maximal overlap the simulations yielded $\sigma_{\mathrm{OL}} \approx 4.5$ dB and $\sigma_{\mathrm{OL}} \approx 2$ dB at minimal overlap. As a compromise between both marginal cases it was proposed to adopt $\sigma_{\mathrm{OL}} = 3$ dB for road traffic noise.

The above conclusions have been derived based on idealized vehicle distributions. As a refinement of the methodology, the standard deviation $\sigma_{\mathrm{OL}}$ shall be determined based on measurement data of real traffic flows. To this purpose traffic census data of two counting stations of the Swiss Federal roads office FEDRO of a measurement period of six months were analyzed on an hourly basis. Both situations had bidirectional traffic on two lanes with a maximum allowed speed of 80 km/h. The total number of analyzed pass-bys over the measurement period amounted to 4.5 Mio vehicles. Figure 1 shows resulting probability density functions of the temporal vehicle spacing for different traffic flows per lane.

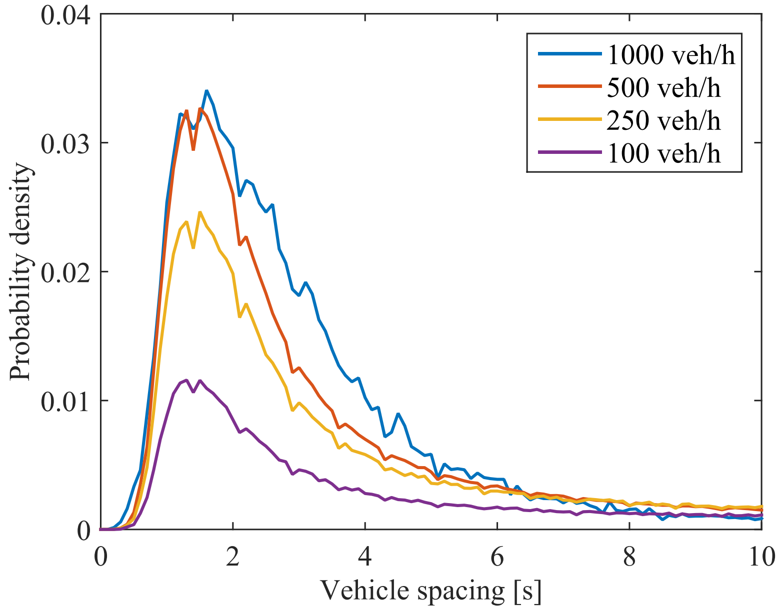


Figure 1 – Probability density functions of the temporal spacing between vehicles for different flows based on traffic census data of two sites with bidirectional traffic on two lanes with a maximum allowed speed of 80 km/h.

The probability density functions according to Figure 1 were again used to produce simulated pass-by measurements (level vs. time pattern). A single vehicle category with constant speed and a source standard deviation $\sigma_0$ = 2 dB was used. The simulation took geometrical spreading and air absorption into account. The pass-by was simulated over a source path aspect angle of 120 degrees. The resulting signals featured a temporal resolution of 0.1 s and a duration of 3600 s.

Three different traffic situations were examined:

a) 1 lane, 60 km/h, total 100 – 1000 veh/h
b) 2 lanes, 80 km/h, total 200 – 2500 veh/h
c) 4 lanes, 120 km/h, total 400 – 6400 veh/h

Receivers were placed in distances of 20, 50, 100, 200, 500 and 1000 m, resulting in 216 different situations. *IR* was derived based on the simulated data and with the calculation (described in section 2) for values of $\sigma_{OL}$ from 0 to 10 dB. Figure 2 shows the resulting mean squared errors for the different parameter settings. Greater deviations occur for very small but also for very large assumed standard deviations. A minimum is reached for $\sigma_{OL}$= 5 dB.

Figure 3 shows a comparison of simulated vs. estimated IRs for standard deviations of the temporal overlap of 0, 3 and 5 dB. When looking at the red crosses it becomes obvious why taking temporal overlaps into account is mandatory to correctly predict *IR* based on calculations. But even with the previously proposed setting of $\sigma_{OL}$= 3 dB a systematic underestimation of the eventfulness of specific exposure situations, especially at small to mid IRs, takes place. Consequently the marginal case of stochastically distributed pass-by times was much more realistic than the assumption of a periodical distribution. The previously proposed approach to apply an average value between periodically and stochastically distributed traffic flows led to a systematic underestimation of the resulting IR.

In cases with low traffic density, typically resulting in high IRs, one would assume that overlapping effects are less relevant and therefore IR to be overestimated by tendency. As can be seen from Figure 3, the opposite is the case. The proposed setting with $\sigma_{OL}$= 5 dB tends to slightly overestimate *IR* at low percentages but underestimate *IR* at high values. Comparing the three settings of $\sigma_{OL}$ in Figure 3 it becomes obvious that the standard deviation for the temporal overlap tends to lose influence with increasing eventfulness. This can be explained by the fact that in a thinned-out traffic most pass-bys are recognized as distinct events, despite their individual variation in level. Consequently the derived setting for the standard deviation for the temporal overlap can be applied even for vehicle categories and situations with only few vehicles per hour.

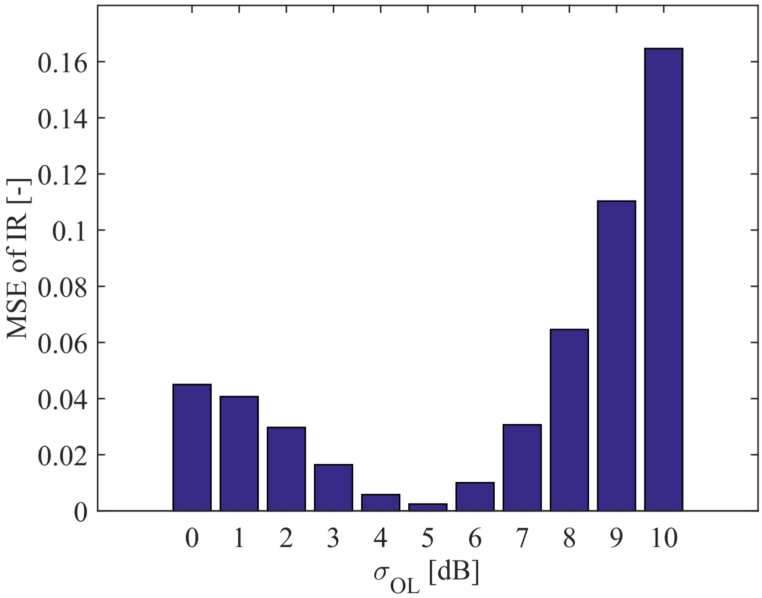


Figure 2 – Mean squared error MSE of simulated vs. calculated *IR* in relation to the setting of $\sigma_{OL}$, the standard deviation for the temporal overlap.

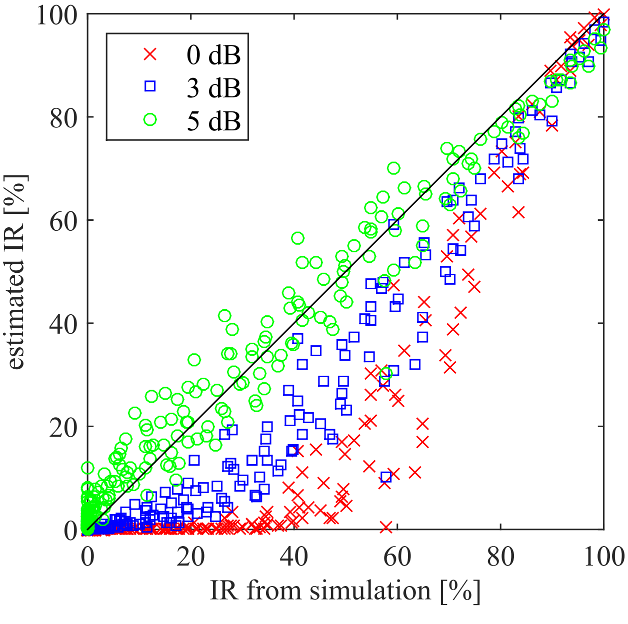


Figure 3 – Comparison of simulated vs. estimated IRs for 216 situations with three different settings of the standard deviation for the temporal overlap $\sigma_{OL}$.

## 4. PARAMETER STUDY

In this section results of a parameter study are shown and discussed to elucidate the behavior of *IR* and to show its dependence on different input parameters. The calculations of *IR* have been performed as described in Section 2.2.

In Figure 4 the dependence of *IR* on traffic flow (number of vehicles per hour) for different source-receiver distances is depicted. Calculations have been performed for a constant speed of 80 km/h and a single vehicle category with a total standard deviation of 5.4 dB, resulting from $\sigma_0 = 2$ dB and $\sigma_{OL} = 5$ dB. High *IR*s representing situations where single pass-by events dominate the acoustic perception can be seen at short distances from the source and with low traffic densities.

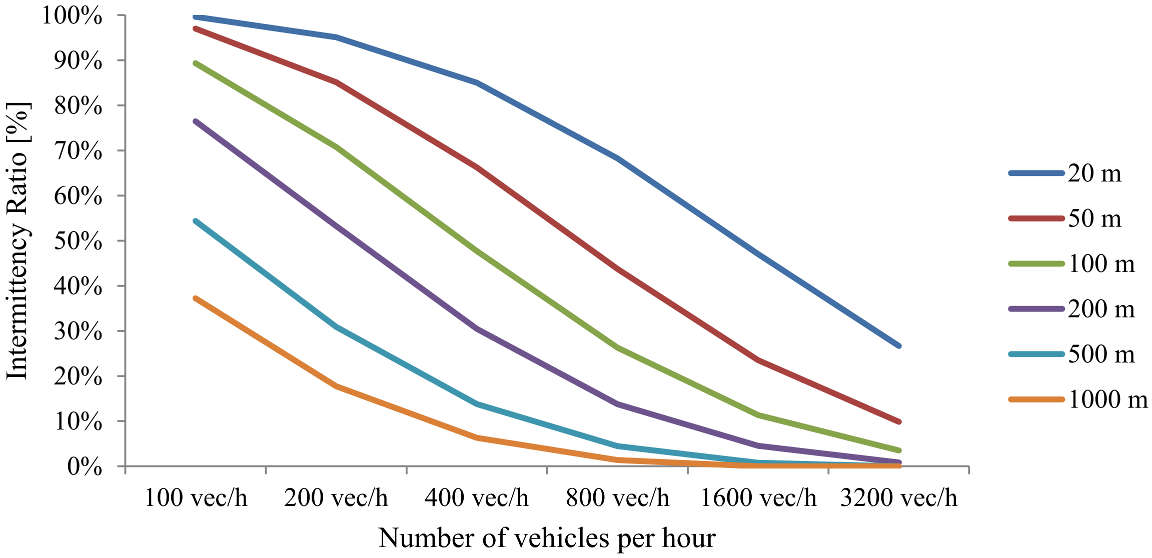


Figure 4 – Dependence of *IR* on traffic flow for different source-receiver distances.

Speed 80 km/h, single vehicle category with $\sigma_{OL} = 5$ dB.

In Figure 5 the effect of different vehicle categories is shown. In addition to the standard category "passenger cars" a second category for "trucks" is introduced with 10 dB higher sound power level per vehicle. Speed and the total standard deviation are kept constant. Results are shown for a distance between road and receiver of 100 m. The case with 0% heavy traffic complies with the result shown in Figure 4 in green. For low traffic flows the percentage of trucks has hardly any influence on *IR* because most of the passenger cars are clearly audible as distinct events. With increasing traffic density however a higher percentage of heavy traffic leads to a substantial increase of *IR*. This can be explained by the fact that loud trucks, even in comparably dense traffic, still clearly stand out from the background noise and hence contribute to the event-related sound dose. The strongest change of *IR* takes place between 0 and 5% heavy traffic. Here the overall Leq is still dominated by the main category of passenger cars. With an increasing share of trucks the total Leq rises, also increasing the threshold *K*. Consequently less pass-bys are counted as events and a greater part of the pass-bys are masked by background noise, leading to a smaller increase of the resulting *IR*.

In Figure 6 a similar depiction is given for the influence of the travelling speed. Again a source-receiver distance of 100 m and single vehicle category with a total standard deviation of 5.4 dB is shown. It can be seen that the travelling speed has a major influence on *IR* with higher IRs for greater velocities. This observation can be explained by the fact that $\Delta L$, i.e., the difference between the maximum level of a single pass-by and its Leq, increases with increasing speed. Consequently more pass-bys exceed the threshold and are counted as events. The source path aspect angle on the other hand has a contrary effect. While the maximum level is only depending on the propagation situation at the shortest distance, the Leq increases with increasing the source path aspect angle. As a consequence a rise of the source path aspect angle leads to an increase of the event threshold and therefore to a decrease of *IR*.

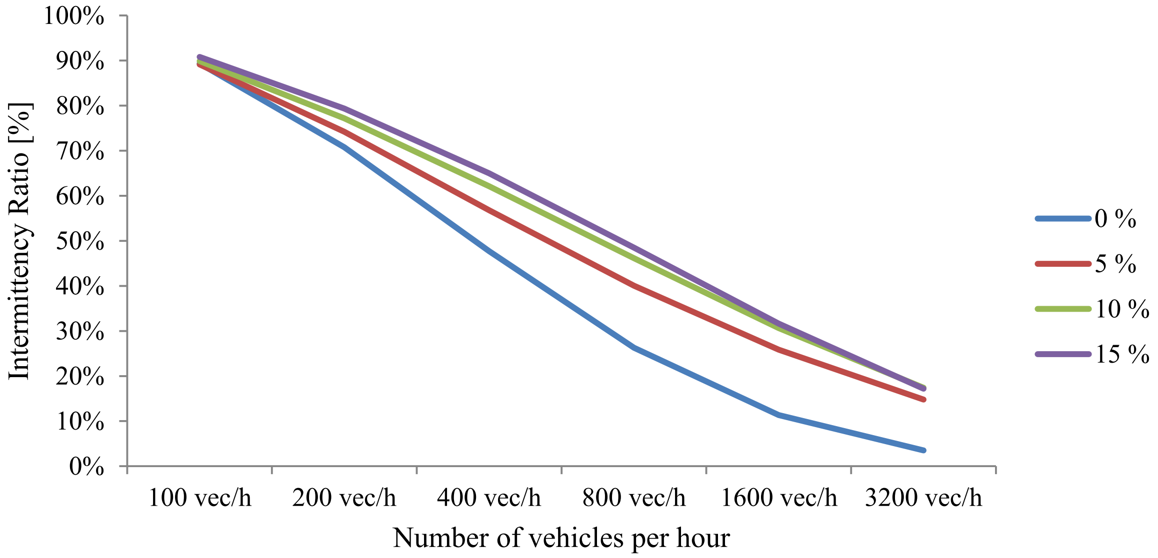


Figure 5 – Dependence of *IR* on the number of vehicles for different percentages of heavy traffic.

Distance 100 m, speed 80 km/h, single vehicle category with $\sigma_{OL}$= 5 dB.

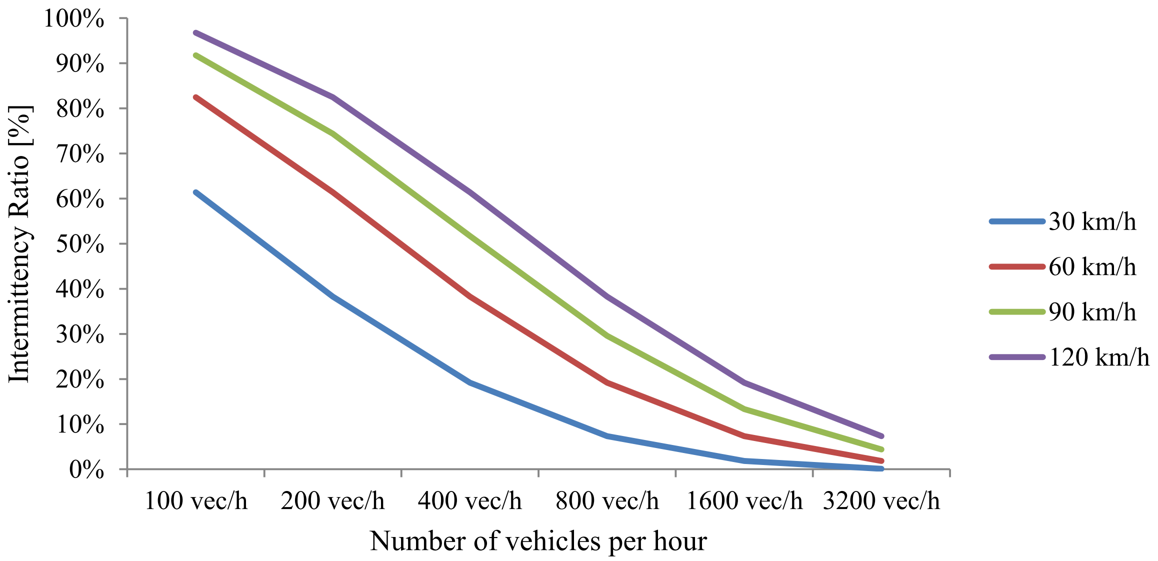


Figure 6 – Dependence of *IR* on traffic flow for different travelling speeds.

Distance 100 m, single vehicle category with $\sigma_{OL}$= 5 dB.

## 5. CONCLUSIONS

An acoustic metric called Intermittency Ratio *IR*, reflecting short-term temporal variations of transportation noise exposure, has been introduced to complement well established acoustic exposure metrics that reflect the average energetic dose. A procedure to estimate *IR* for road traffic noise has been presented and a parameter optimization for the consideration of temporal overlapping effects of single vehicles has been carried out. In a parameter study the behavior of *IR* was investigated, showing its dependency on source-receiver distance, traffic flow, percentage of heavy traffic and travelling speed. It could be shown that *IR* has a smooth behavior and intuitively correctly reproduces the characteristics of transportation noise, yielding high values in sound exposure situations that are generally assessed as "event-dominated" and low values in situations with a nearly constant level due to the overlay of numerous sound sources of comparable level.

The method to calculate *IR* has deliberately been defined in a rather simplified way with the goal of facilitating an implementation in standard engineering tools for sound propagation and as consequence allowing for an application on a broader basis, among others in epidemiological studies. It is therefore less sophisticated than other recently published approaches for example by de Coensel (20) or Heimann et al. (21).

In particular, the slope of rise of level is not explicitly accounted for. It can be assumed that the slope of rise might have a relevant impact on the perception of pass-by events both during sleep (5, 6, 22) and wakefulness (23-25). The slope of rise of level generally increases with increasing speed of the source and with decreasing distance and traffic density – a behavior which is also featured by *IR*. Consequently it can be concluded that at least the general trend of the assumed effect of the slope of rise of level is reproduced correctly.

We see a potential for this new metric, in addition to existing metrics, in investigating the role of short-term temporal patterns of transportation noise in epidemiological and socio-acoustic studies. The outcome however remains open, especially in relation to wakefulness. Situations with high IR values are often characterized by dominant single events which are likely to draw higher attention and therefore presumably also higher annoyance. The same situations, on the other hand, are characterized by longer periods of quietness which might have the opposite effect. This, for example, is one of the explanations for the "rail bonus" which is inherent to many railway noise regulations in Europe (26, 27). Further investigations of SiRENE aim to elucidate if *IR* serves variance explanation in annoyance surveys, and evaluate if *IR* is a valuable additional predictor in epidemiological studies on long-term health effects and sleep disturbances.

## ACKNOWLEDGEMENTS

This work was undertaken within the framework of the SiRENE study - Short and Long Term Effects of Transportation Noise Exposure, funded by the Swiss National Science Foundation (Grant No. CRSII3 147635). The authors gratefully acknowledge the financial support from SNF, and the scientific input and advice of colleagues working on SiRENE.

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