Advanced Tools for Traffic Noise Modelling and Prediction

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Abstract: - Environmental impact studies are strongly related to road traffic noise, especially in urban areas. A long term exposure to road traffic noise, in fact, can lead to relevant effects, both auditory (e.g. sleep disturbance, hearing loss, etc.) or not auditory (e.g. stress, anxiety, cardiovascular problems, etc.). A proper modelling of noise production and propagation is a challenging issue, especially in areas where the complexity of sources, receivers and other objects makes difficult to use standard predictive formulas, such as the usual Traffic Noise predictive Models (TNMs). The collection of experimental data is always advisable, in order to control the predictive tools and eventually tune their parameters. In this paper, the author presents a set of advanced tools for noise modelling, particularly aimed at the prediction of non-conventional situations, such as road intersections, traffic jams, extreme traffic flow, etc., where the standard TNMs usually fail. The main idea is to implement a dynamical approach in the traffic noise prediction, i.e. to include the dependence of noise emission by kinematical parameters, such as speed, position and eventually acceleration. This can be achieved by means of different approaches, some of them resumed in the paper, for instance cellular automata, traffic theory (Fundamental Diagram), source power dependence from the speed, etc.. The implementation of these models in easy to use tools represents the new horizon in traffic noise prediction.

Key-Words: - Noise Control, Road Traffic Noise, Traffic Theory, Dynamical Models.

1 Introduction

The environmental impact control is nowadays one of the most important problem in urban areas. The European Community (EC) settled, funded and developed the Harmonoise and IMAGINE projects (*Improved Methods for the Assessment of the Generic Impact of Noise in the Environment*) [1, 2] with the aim of furnishing an uniform approach to community noise and common standard criteria for monitoring and control of noise impact on human activities, in particular for developing predictive models.

The relevant sources that are to be considered are transportation infrastructures, industrial settlements and anthropic activities. In particular, scientific literature reports many studies, both theoretical and experimental, concerning monitoring and reduction of noise produced by transportation means, especially road networks, railways and airports (see for instance [3-12]). It's reasonable to affirm that in urban areas, road traffic noise is the most relevant source, since airports are usually placed outside the downtowns and railways are usually designed to move out from the centre of the cities and rarely cross the residential districts. Medium-big size cities may be equipped with subways that do not hardly affect the environment from the acoustical point of view.

The annoyance produced by noise pollution has been studied and documented in scientific literature (see for instance [13, 14]). The exposure to noise, in general, may affect mental and physical health in terms of sleep and/or conversation disturbance, hearing loss, cardiovascular problems, anxiety and stress, etc.. Thus, the need for monitoring and eventually predicting road traffic noise is evident.

Traffic Noise predictive Models (TNMs) are usually adopted to control the noise level in a certain areas where road network is highly present. These TNMs are also used to define risk classes for each area, according to the purpose of the activities therein, and to adopt the zoning required by European regulation. Experimental measurements are performed together with TNM simulation, especially when the number and typology of sources make difficult to use a single predictive model. Sometimes predictive commercial software are also adopted in the environmental study, since they take into account several sources at the same time.

TNMs used nowadays are barely universal, in the sense that since they are based on a statistical approach, they strongly depend on the data used in the fit and in the parameters tuning. The shortcomings of these models are highlighted and discussed on a review process and experimental data comparison basis in [15, 16], and herein briefly described in section 2.

The aim of this paper is to highlight the state of the art of road traffic noise prediction and to show that new models, based on a dynamical approach, can be developed and used in order to better simulate the intrinsic random features of traffic phenomenon.

2 Basic concepts on road traffic noise

Road traffic noise may depend by several parameters. These parameters can be "intrinsic" of the phenomenon, i.e. related to noise production and propagation processes, or "specific" of the area under investigation. To the first class, belong the traffic volume (number of vehicles), the traffic flow typology, the vehicles typology, the road and pavement features, the speed, etc.. In the second class, one can find the kind of vehicles, the speed limits, the amount and typologies of road intersections, the emission threshold fixed by regulation, the vehicles maintenance duties, the driving skills and habits, etc..

The statistical Traffic Noise Models (TNMs) used nowadays are usually based on a fit performed on experimental data collected in a defined place. This, of course, results in a loosing of generality because the resulting formulas are dependent on the area where data have been collected, i.e. they do not consider the variability of the second class parameters described above.

A review of the main TNMs can be found in [15] and some of them have been tested on experimental data in [16]. The results are shown in Fig. 1 where the predictions of different models have been plotted versus the hourly number of vehicles, i.e. the hourly vehicles flow. In Fig. 2, instead, the levels simulated with different TNMs have been plotted versus the corresponding experimental data. The best the predictions are, the closer to the bisector should be the points.

Even if the prediction may strongly fluctuate, these TNMs are largely adopted in many issues because of the easiness of usage, especially when a high sensibility is not needed.

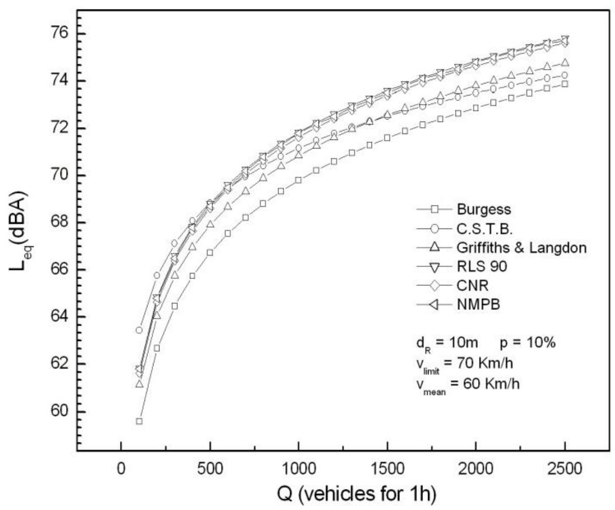

Fig. 1: Comparison between different Traffic Noise Models, with fixed parameters (see legenda) [15].

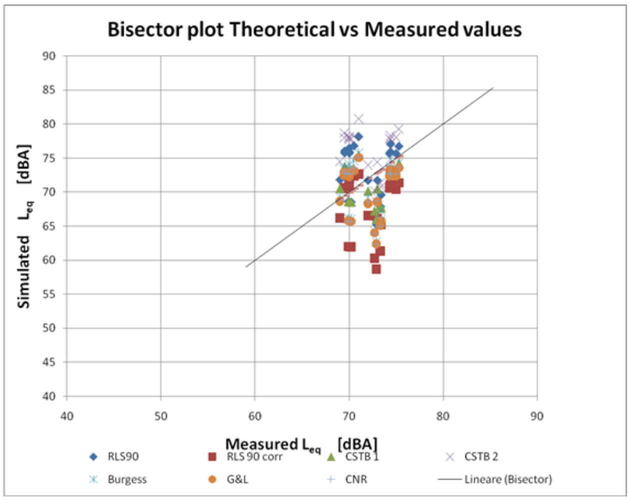

Fig. 2: Simulated versus Measured L_{eq}, for both sites and all the measurements, [16].

The equivalent levels evaluated with statistical TNMs are particularly helpful in standard conditions of traffic flow, i.e. when vehicles run more or less with a constant speed, without abrupt changes, and in absence of any relevant conflicting point, i.e. an intersection. The presence of intersections has been analysed in [6, 7] in terms of experimental data and predictive software approach.

The main conclusion of all these studies is that the prediction of noise produced by standard road traffic, i.e. without strong changes in vehicles flow and speed, can be roughly performed with many statistical TNMs, that can all be written in a compact form as follow:

$$L_{eq} = A \log Q\left[1 + \frac{p}{100}(n-1)\right] + b\log(d) + C \quad (1)$$

where L_{eq} is the acoustic equivalent level, Q is traffic volume (flow) in vehicles per hour, P is the percentage of heavy vehicles, n is the acoustical equivalent and d is the distance from observation point to center of the traffic lane. The A, b and C coefficients may be derived, as already described above, for a fixed investigated area, by linear regression methods on many L_{eq} data taken at different traffic flows (Q, P) and distances (d). The acoustical equivalent, n, (defined as the number of light vehicle that generate the same acoustic energy of a heavy one) can be estimated both by regression method or by single vehicle emission measurements.

Of course the statistical approach is useful for practical application but does not include many features of the phenomenon that can affect the noise production and propagation, such as the different vehicles' speed and conditions, the road maintenance status, the speed limits, etc.. Some of these parameters have been considered in international regulation, usually by means of additional corrections (see for instance [17, 18]).

An improvement of the statistical formula (1) that includes the dependence from the speed has been exploited by Iannone et al. in [8].

The procedure needs as input the dependence of source power level from speed. In this paper the author will consider the experimental study of Steven, performed for the German Environmental Agency [19]. The results are resumed in Fig. 3, where the dependence of L_{max} from vehicle speed is reported for several vehicle typologies. It's easy to notice that cars and Light Duty Vehicles (LDV) present a log slope, while High Duty Vehicles (HDV, different kinds), buses, motorcycles and mopeds, exhibit a linear slope. It is reasonable to assume that the L_{max} dependence from speed can be applied to L_W, i.e. the power of the source (see for instance [20]).

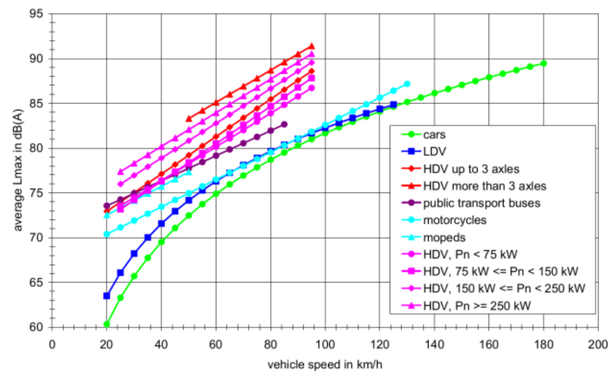

Fig. 3: Average Lmax dependence from vehicle speed [19].

This result, that is achieved by means of an experimental approach, can be resumed, simplifying in two categories, light and heavy vehicles, as follows:

$$\begin{aligned} L_{w,L}(v) &= \alpha_L + \beta_L\, Log(v) \\ L_{w,P}(v) &= \alpha_P + \beta_P\, v \end{aligned} \qquad (2)$$

Once the power of the source is obtained, the single transit emission, in particular the Single Event Level (SEL), can be estimated assuming that the noise level evaluated on one second time range (SEL) is the noise level of a pointlike source (single vehicle assumption) with given power L_W and source-receiver distance equal to road-receiver spacing (see [8] for details):

$$\begin{aligned} SEL_L(d,v) &= \alpha_L + \beta_L Log(v) - 20Log d - 11 \\ SEL_P(d,v) &= \alpha_P + \beta_P v - 20Log d - 11 \end{aligned}$$

Performing a sum over the number of vehicles, with different index depending on vehicle typologies, and evaluating on one hour time range, the hourly L_{eq} is obtained:

$$L_{eq}^{(1h)} = 10Log\frac{1}{3600} + 10Log\left[\sum_{i=1}^{N_L} 10^{\frac{SEL_{L,i}}{10}} + \sum_{j=1}^{N_P} 10^{\frac{SEL_{P,j}}{10}}\right]$$

If one assumes the acoustical energetic content of each transit to be approximately constant (e.g. continuous flow condition, regular volumes, little variations in the speed distribution, etc.), then $SEL_{L/P,i/j}$ does not depend anymore on the i or j index. Thus, one can write:

$$\sum_{i=1}^{N_L} 10^{\frac{SEL_{L,i}}{10}} + \sum_{j=1}^{N_P} 10^{\frac{SEL_{P,j}}{10}} = N_L\, 10^{\frac{SEL_L}{10}} + N_P\, 10^{\frac{SEL_P}{10}}$$

Being generally $SEL_P > SEL_L$, one can write:

$$N_L\, 10^{\frac{SEL_L}{10}} + N_P\, 10^{\frac{SEL_P}{10}} = 10^{\frac{SEL_L}{10}}\left(N_L + n(v)\cdot N_P\right) \qquad (3)$$

where we define

$$n(v) = 10^{\frac{\Delta SEL}{10}} = 10^{\frac{SEL_P - SEL_L}{10}} \qquad (4)$$

$n(v)$ has the same meaning of the acoustic equivalent n in the general statistic TNM formula

(1), i.e. the number of light vehicles needed to obtain the same noise of a heavy one.

Thus, considering :

$$\Delta SEL(v) = \alpha_P + \beta_P v - \alpha_L - \beta_L Log(v)$$

One can write:

$$n(v) = 10^{\frac{\alpha_P + \beta_P v - \alpha_L - \beta_L Log(v)}{10}}$$

This approach exploits that, in this model, the acoustic equivalent depends on the average flow speed and traffic typology, thus the constant values obtained by linear regression or a-priori assumption are just an approximation.

The $n(v)$ function is plotted in Fig. 4, considering the fit values presented in [8] and in cruising state. One can easily notice that, for average speed typical of urban area, i.e. about 40-50 km/h, the acoustic equivalent is bounded between 6 and 4, in a very good agreement with values provided in literature, for instance by CNR and Peretti et al. models trough experimental measurements [21, 22].

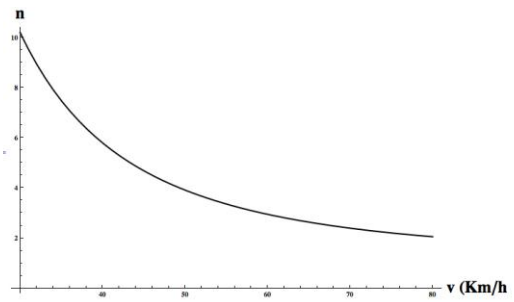

Fig. 4: Acoustic equivalent n versus average flow speed for cruising regime.

Finally we obtain the following expression:

$$L_{eq}^{(1h)} = 10Log[N_L + n(v)N_P] + \alpha_L + \beta_L Log(v) + \\ -20Log(d) - 47{,}563 \quad (5)$$

that can be related to formula (1) by the position:

$$Q_{eq}^{1h} = N_L + n(v)N_P,$$
$$A = 10, \quad b = -20,$$
$$C = \alpha_L + \beta_L Log(v) - 47{,}5638.$$

This time the traffic flow Q (in particular the acoustic equivalent) and the C parameter depend on speed.

3 Modelling of road traffic noise

Usually road traffic noise is generated by each car that transits on a given road. In particular, moving car noise is produced mainly by the engine, the exhaust system, the contact between tire and pavement. Beside car sources, the aerodynamic noise must be considered, especially when vehicle speed is high, e.g. in highways and extra urban roads. The combination of these effects results in a quite complex source that cannot be easily modeled in all its features. The frequency spectrum, for instance, is affected by the leading noise source.

The most reasonable choice, thus, is to consider each car as a single source, with a given sound power level. Usually TNMs consider the collective movement of several car as an incoherent line source [23-27].

The two interim models used in noise mapping for road traffic and rail noise are respectively the French model [28, 29] and the Dutch rail model [30]. Since they use a different approach in the integration of the line source, i.e. a point approach for the French model and a line approach for the Dutch one, in [31] the difference between point and line approximation is investigated, in particular on the numerical point of view, and an optimized method is presented.

In [32] Guarnaccia et al. present a study on the "linearity degree" of road traffic based on an experimental campaign and, even if more comparison and analysis must be performed, the first results show that the linear approximation is confirmed by measurements taken in that specific conditions.

Let us also recall an important equivalence demonstrated by Quartieri et al., [33]. The acoustical field produced by a linear source dx is equivalent to the field produced by a curved source ds in the center P of the circumference that includes the latter source, tangent to the line where the former source lays (see Fig. 5).

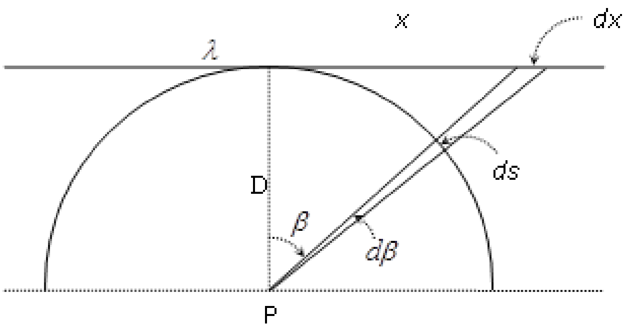

Fig. 5: Infinitesimal sources position, [33].

This result is particularly helpful in areas where a low density of buildings is present. A single small bunch of buildings, in fact, placed along a highway or a railway, is affected by a quite strong noise. Considering the above equivalence, one can assume that, with a good approximation, the linear source can be "replaced", in the modeling of the environment, by the curved one. This means that, for screening purposes, one should consider a quite relevant lower length of source, that results, for instance, in a relevant lowering of barriers length or other mitigation action.

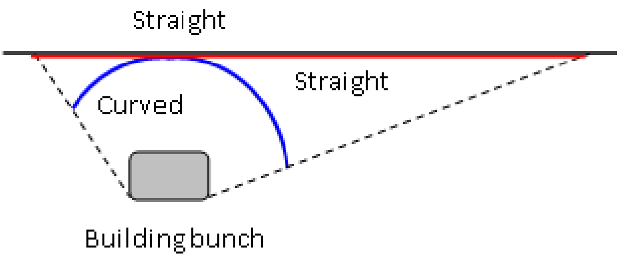

Fig. 6: Practical example of linear and curved sources position, [33].

4 Non-standard conditions: intersection case study

One of the most relevant situation in which the traffic flow cannot be considered "standard", is when the road presents conflicting points. The intersection impact on traffic noise generation has been deeply studied in literature (see for instance [4] and [5]).

In this paper, the author recalls the results obtained in [6, 7] and gives further elements to approach the noise issues in intersections.

In particular, let us recall the equivalence that can be pursued between traffic flow and electrical current, when considering a conflicting point. Each vehicle, in fact, can be considered as a current element, i.e. a charge, flowing in a circuit and, when entering an intersection, approaching a node of the net. Thus, the Kirchhoff Current Law (KCL) can be depicted for vehicle flow: vehicles entering or exiting the intersection can be considered respectively as currents entering or exiting a node of the circuit. Even if the KCL is usually used in a node, more in general, it is valid for any closed surface in which the node is placed, since it is related to flux concept, thus the parallelism between node and intersection is definitely adequate.

Of course, one can affirm that vehicles are not allowed to park or to stop in an intersection, and, consequently, no vehicle can enter the intersection without exiting or vice versa. This means that in the intersection a kind of continuity equation related to vehicles density stays, in absence of sources and/or wells.

Standing this analogy, one can state the following:

Proposition 1: "*the sum of the number of vehicles that enters a given intersection from any road converging in that point, is equal to the sum of the number of vehicles that exits that intersection from any branch*".

The above proposition can be resumed as follows:

$$\sum_n Q_n^{IN} = \sum_m Q_m^{OUT} \qquad (6)$$

with n and m respectively the number of entering and exiting branches of the intersection.

This very simple analogy can be used in the measurement survey design, to optimize the collection of traffic flow data, usually performed by human operators, and/or to estimate the expected ratio of vehicle flow in each branch of the intersection.

In [7] the above proposition has been used to optimize the number of operators in a measurement survey performed in a relevant intersection placed at the entrance of the University of Salerno (Fig. 7). The measurement results have been compared to a software prediction, in order to tune the model and to be able to simulate new configurations for the intersection. The roundabout configuration is suggested by literature as one of the best solution to be adopted, provided that flows and geometry of the intersection are suitable with this solution.

In Fig. 8, the noise map produced by the software simulation of the roundabout intersection is presented. The flows have been chosen according to the previous simulation and the roundabout geometry has been designed according to the legislative requirements [34, 35].

The introduction of the roundabout leads to a lowering of the L_{eq} of about 1 dBA, which is consistent with values found in literature.

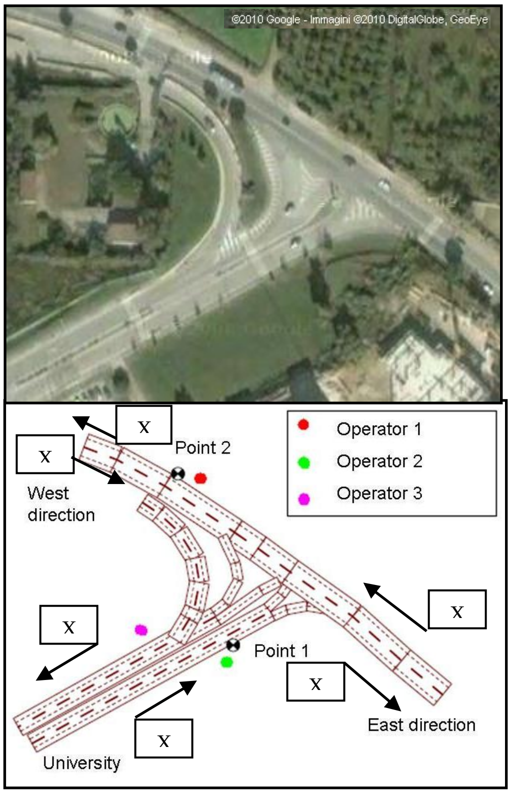

Fig. 7: Case study intersection taken from Google© and implementation of the intersection in the predictive software, with measurement points and operators position

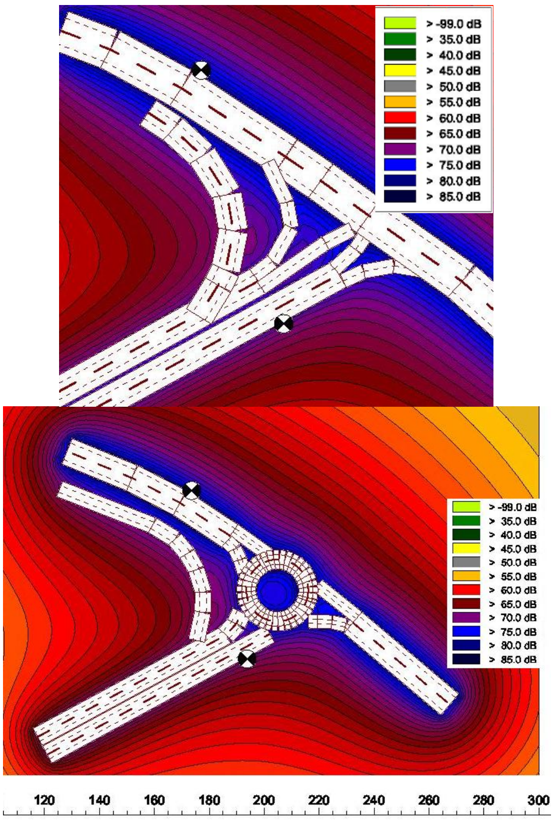

Fig. 8: Noise maps in the real and the roundabout configurations.

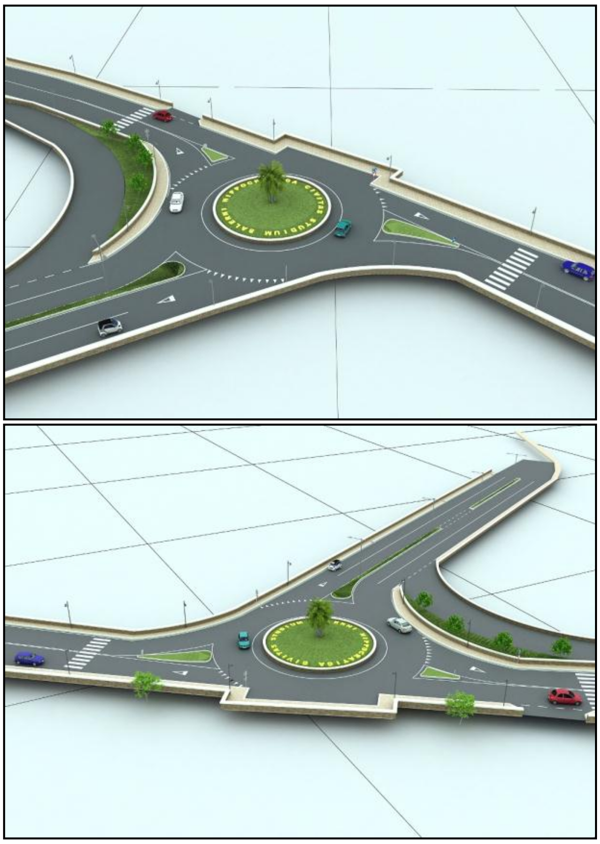

Fig. 9: 3D render of roundabout configuration insertion.

5 Dynamical models of road traffic noise

The main shortcoming of the actual TNMs, as described in the previous sections, is the statistic approach that strongly depends on the data used for the fit procedure. These TNMs don't take into account the intrinsic random nature of traffic flow, in the sense that they don't take care of how vehicles really run, considering only how many they are. One of the possibility to overcome this problem consists in considering the dynamics of each vehicle. In [36], for instance, Can et al. described in details the dynamical evaluation of traffic noise, focusing on the influence of traffic and on the noise source representation.

Evaluating the position and the speed of each transiting vehicle, and knowing the relation between the sound power level and the speed, it can be easy to compute the acoustical energy produced by the single vehicle. Therefore, by modeling the propagation from the source to the receiver, one can estimate the noise measured at a given point or in a certain area under investigation.

This very simple concept is not yet conveniently implemented in noise prediction because of many reasons. First of all, it is not easy to evaluate the dependence between sound power level and speed. Some experimental and theoretical studies have been performed (see for instance [37]) and can be used as a reference for further investigation.

Then, especially for high traffic volume, it is difficult to handle a great number of variables, that are the position and the speed of each vehicle.

In addition, even if this approach can evidently improve the prediction in "not standard" conditions (i.e. in traffic jams, not fluid flow conditions, extremely low or high traffic volumes, etc.), it must be demonstrated that the strong computational effort and the complexity of these tools can quantitatively lead to much more precise results in standard conditions, in comparison with common TNMs. For instance in [38] the authors compares three urban traffic noise assessment approaches: a static calculation based on mean speeds and flow rates, a refined static calculation based on mean kinematics patterns, and a whole dynamic noise estimation model that considers vehicle propagation. Even if the second approach is sufficient for $L_{A,eq}$ estimation in most of cases, a complete dynamic model improves noise estimation since it considers vehicle interactions on the road network.

A method to overcome the computational problems is to use advanced tools, both statistical and/or stochastic, such as Neural Networks, Cellular Automata, Montecarlo approach, etc..

In the next subsections, three different approaches will be briefly presented.

5.1. Cellular Automata model

In [39], the authors modeled the single lane traffic by a deterministic Fukui-Ishibashi Cellular Automata model [40], evaluating equivalent global noise level directly by the traffic dynamics.

The results are reported in Fig. 10 where two simulations are presented, with two different vehicles densities *k*. It is easy to see that a higher density (bottom plot) produces a lower average noise level, because of the fact that the flow is in congested state, thus reducing its average speed. On the contrary, the top plot shows a free flow scenario, with a higher average noise level due to higher average speed of the flow.

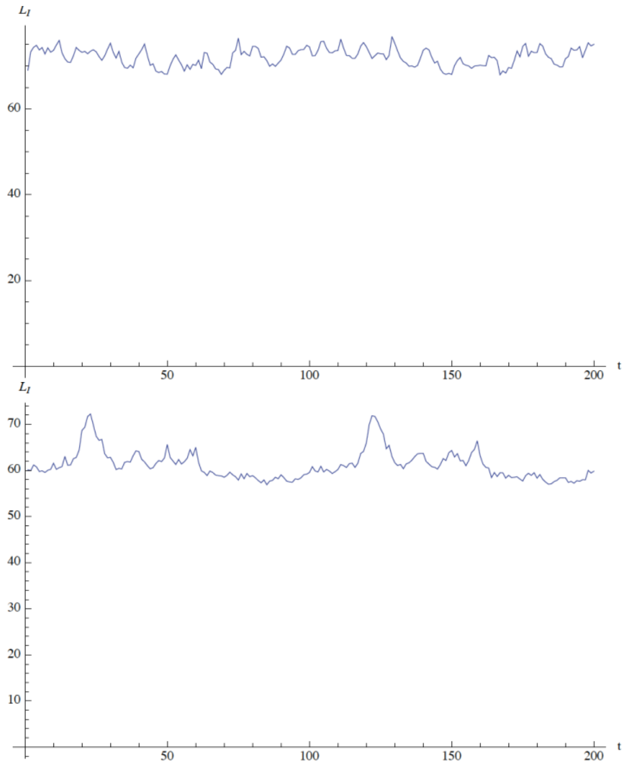

Fig. 10: Noise level at the receiver (d = 10 m) as function of time for *k* = 0,2 (top) and *k* = 0,7 (bottom), evaluated using Fukui-Ishibashi Cellular Automata model and noise level evaluation, [33].

5.2. Speed distribution: stochastic approach

In [41], Iannone et al. developed a model based on a speed distribution study. The set of speeds of vehicles, when running in fluid flow conditions, are distributed according to a normal distribution [42-44]. Thus, one can simulate the transit of the single vehicle by randomly extracting a speed from this distribution. Then, according to the relations between sound power level and speed, the noise produced by each vehicle is evaluated at a certain distance from the receiver. The last step consists in the time averaging, i.e. the evaluation of the Single Event Level (SEL) and of the equivalent level (L_{eq}), as defined by regulation [17]. The results of this procedure have been compared with experimental data, showing a good agreement.

In addition non-symmetric distributions, such as the Beta and the Chi-Square, have been introduced in order to model pulsed accelerated and decelerated flows. This is consistent with literature experimental studies, such as, for instance, [45].

5.3. Traffic Dynamics theory

Traffic theory introduces a diagram based on the relation between flow and density, the so called "Fundamental Diagram". In [46], Iannone et al. presented the integration between a "car-following" dynamic model for single lane traffic and noise prediction, by postulating the equations of a "Noise Fundamental Diagram".

The final expressions for the theoretical dependence of equivalent level from vehicle density, for the three postulates of "car-following" model, that are the basis for the construction of a Traffic Noise Fundamental Diagram, are:

$$L_{eq}^{(1h)} = 10Log\left(1 - \frac{k}{k_j}\right) + L_{w,L}(\bar{v}) + \\ - 20Log(d) + \tilde{C}_1 \quad (7)$$

$$L_{eq}^{(1h)} = 10Log\left(k \log\frac{k_j}{k}\right) + L_{w,L}(\bar{v}) + \\ - 20Log(d) + \tilde{C}_2 \quad (8)$$

$$L_{eq}^{(1h)} = 10Log\left(ke^{-C_3 k}\right) + L_{w,L}(\bar{v}) + \\ - 20Log(d) + \tilde{C}_3 \quad (91)$$

where k is the flow density, $\bar{v}$ is the mean speed, d is the source-receiver distance, C_3 and $\tilde{C}_\iota$ are constants.

The possibility to predict the noise levels on a road, given the density and the speed of the flow opens new perspectives in environmental impact study and traffic noise assessment.

6 Conclusions

In this paper, the author highlighted the problem of road traffic noise in environmental impact study. The actual methodologies have been resumed and literature papers have been recalled to report the main shortcomings of statistical approaches. The results of these models, in fact, are strongly affected by experimental data fitting procedure, since they don't take into account the intrinsic random nature of traffic flow. The acoustical phenomenon, in fact, depends on many parameters, some of them dependent on the area where the phenomenon occurs. This approach fails especially in "not standard" conditions, i.e. when the flow is not fluid or when the number of vehicles is very low (or very high).

A dynamical approach, able to evaluate the emission of the single vehicle by considering its position and speed, is needed to better model the road traffic noise phenomenon. Thus, the integration between dynamic representation of traffic flows and noise emission laws seems to be the future for road traffic noise prediction. Some studies have been reported, highlighting that these new models lead to simulations more adherent with reality.

Future steps of this approach can be the correlation of traffic noise with air pollution, since several studies already model the air pollutant emissions in relation to the vehicle dynamics.

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