Traffic noise forecasting tools: a mathematical model

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Abstract: - This study is introduced as a moment of reflection within the bounds of the methodologies for estimating sound pressure levels emitted by traffic in urban areas. It starts with an analysis of the phonometric measurements campaigns carried out in the urban area of Crotone. The results obtained by advanced simulation techniques show a good reliability of the prediction model as a function of the considered parameters, which are the traffic flow, the percentage of heavy vehicles detected and positioning of noise sources. Taking into account the results of previous studies [3] [12], a predictive model to estimate traffic noise in a city of medium size has been specified and calibrated. In order to reach its final validation, the model can be applied to other urban settings.

Key-Words: - Prediction models, Urban traffic, Noise pollution, Heavy vehicles

1 Introduction

Numerous studies have been conducted under the definition of models to predict the noise generated by vehicular traffic. Studies were undertaken on the assumption that in urban areas almost all the sound pressure levels, both in daytime and at night time, is due to passing vehicles. In fact, as early as the seventies, in most industrialized countries, laws were passed aimed at reducing noise pollution in urban areas, defining the permissible sound pressure levels and introducing, as an index of disturbance, the equivalent sound level (Leq). In recent decades, for these reasons, research in acoustics was directed mainly to the study of correlations on the prediction of noise generated by vehicular traffic in terms of average sound level.

The working hypothesis started from the data analysis of the phonometric campaigns, conducted for over fifty years and reported in the literature, with which researchers have come to define predictive models able, under suitable conditions, to estimate a phenomenon acoustic with an acceptable degree of reliability. And, while there is a line of research that aims to demonstrate the inadequacy of the model data, they also reveal themselves, if properly calibrated, very useful, particularly for the purposes of planning and urban design since they can provide valuable tools decision support. The development of models for predicting noise from vehicular traffic, commonly referred to by its acronym, TNM (Traffic Noise Model) has therefore become an area of scientific debate in which there is a chance to address noise problems of different nature, since the number and complexity of variables involved.

In the present study parameters depending on the characteristics of road traffic, the percentage of heavy vehicles and, more interestingly, the distance of the moving source have been, in particular, considered. It is useful to reiterate that a universal model descriptive of the acoustic phenomenon in its entirety does not exist, because the large number of parameters to be considered makes this operation very complex. The model presented in this research is simplified, following a statistical approach and has an acceptable degree of accuracy.

2 State of art

Traffic noise is a component of environmental noise and is the result of the sum of various types of noise from traffic sources (e.g., cars, buses, trains, etc.).

Road traffic noise is the component of traffic noise that comprises the sources of traffic on a road, whether caused by passing (circulation and parking) or by working (highway works). The former sources are discontinuous, since the sound levels grow as the source approaches the point of observation, reaches a maximum peak, and decreases as the source moves away, until it reaches the level of background noise.
There are many parameters directly or inversely correlated with traffic noise levels.

Techniques to predict noise levels generated by road traffic from parameters such as speed, traffic flow, the slope of a road, infrastructure characteristics, etc are very useful for territorial planning.

The researches conducted on noise level prediction, in different countries, have led to the development of various models. Suksaard et al. [39] studied a model to predict the environmental impact of traffic noise based on two vehicles classes. A road traffic noise prediction method for northern European countries was discussed by Bendtsen [4]. A noise prediction model based on Monte-Carlo approach was proposed by Lam and Tam [23].

The most important variables considered in the development of mathematical models are traffic flow rate and composition [7], [2]. Increased traffic volume, in terms of vehicles per hour, causes an increase in the noise level [32].

Li et al. [25] developed a GIS based road traffic noise prediction model. Pamanikabud and Tansatcha [31] have also used GIS for analyzing highway traffic noise.

Several models have been developed via a regression analysis of experimental data, from fundamental variables such as traffic flow, speed of vehicles and sound emission level [37], [1].

An exhaustive discussion on early and recent traffic noise prediction models can be found in the review by Steele [36].

A statistical model to estimate road traffic noise in an urban setting was applied by Calixto et al. [7]. Cirianni and Leonardi [11] proposed an ANFIS model to estimate the traffic noise in urban condition in an Italian context. The model developed in Barone et al. [3] starts from a modeling base previously defined and validated through a survey campaign by the same research group [12].

The prediction model presented, continues to direct towards the development of an integrated modeling, that is to include within a single model the flow characteristics, urban surroundings and the specific road surface characteristics.

The regression model simulates, with statistically reliable results, the equivalent level \( L_{eq} \) by three specific variables: the average velocity of flow \( V \) the flow, \( H \) relating to the urban context and \( Mat \) relating to the road surface.

The input data are therefore known, because predicted or assumed in the design and verified during the measurement campaigns.

Several studies on the external noise have led to the formulation of three main types of models:
- models that correlate the \( L_{eq} \) with geometrical and traffic parameters;
- models that assess the \( L_{eq} \) as the sum of individual events;
- experimental models.

The models based on the correlation between traffic and geometrical parameters, with the \( L_{eq} \) measured in experimental studies, generally have as input the traffic flow, the composition and the average speed of the vehicular current, the slope, the ratio between the height and the distance of the buildings and sometimes the road bed conditions. Numerous indices have been defined to describe the degree of disturbance due to vehicular traffic, among them the most significant are: \( L_1 \), \( L_{10} \), \( L_{50} \), \( L_{90} \). They represent the sound pressure level exceeded in the 1%, 10%, 50% and 90% of the detection time.

It should be noted that generally all the proposed models are derived from a statistical analysis of data collected and generally from the best approximation of experimental results, given the extreme difficulty or even the impossibility to develop models by analytical considerations on the phenomenon characteristics.

The figure shows some of the proposed models to estimate the equivalent level.

\[
\begin{align*}
L_{eq} &= 49.5 + 0.21V + 12.2 \log (F + 0.067) \\
L_{eq} &= 10 \log (V + 20) + 20 \log (d + 0.067) \\
L_{eq} &= -17.5 - 10 \log (F + 0.067) - 31.8 \log (H + 0.1) \\
L_{eq} &= 38 + 15 \log (F + 0.067) - 10 \log (L + 6M + 10H) - 4.50 \log (d - 1) \\
L_{eq} &= 51 + 10 \log (V + 0.067) + 0.3 \log (d - 1) \\
L_{eq} &= 55.5 + 6 \log (V + 0.067) + 0.3 \log (d - 1) \\
L_{eq} &= 55.7 - 0.05V + 12.2 \log (F + 0.067) - 12.7 \log (L + 0.067) \\
L_{eq} &= 52 + 10 \log (F + 0.067) + 0.3 \log (d - 1) \\
L_{eq} &= 50 + 10 \log (F + 0.067) + 0.3 \log (d - 1) \\
L_{eq} &= 28 + 0.65L + 0.021(L + 0.079(L + 0.0167(L + 0.0023(L + 0.0005L))) \\
L_{eq} &= 20 + 20 \log (V + 0.067) + 10 \log (d + 0.067) \\
L_{eq} &= 55.2 + 6 \log (V + 0.067) + 11.7 \log (L + 6M + 10H) - 4.50 \log (d - 1) \\
L_{eq} &= 51 + 10 \log (V + 0.067) + 0.3 \log (d - 1) \\
L_{eq} &= 52 + 10 \log (F + 0.067) + 0.3 \log (d - 1) \\
L_{eq} &= 55.5 + 6 \log (V + 0.067) + 0.3 \log (d - 1) \\
L_{eq} &= 55.7 - 0.05V + 12.2 \log (F + 0.067) - 12.7 \log (L + 0.067) \\
L_{eq} &= 52 + 10 \log (F + 0.067) + 0.3 \log (d - 1) \\
L_{eq} &= 50 + 10 \log (F + 0.067) + 0.3 \log (d - 1) \\
\end{align*}
\]

Fig. 1 - Road traffic noise prediction models to estimate the equivalent level

In the second group of prediction models the overall level is calculated as the sum of the individual sound events that occur in a time interval \( T \). These models are based on the calculation of SEL (Single Event Level).

A third type of models for noise prediction is based on the realization of numerical models which reproduces the urban environment.

Starting from the literature, a review has been conducted about noise model and a selection in reference to simulators used for the prediction of traffic noise has been made.
Some models have been identified and listed in Table 1 below.

### Table 1 - Traffic noise models

<table>
<thead>
<tr>
<th>N.</th>
<th>Developed</th>
<th>Produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Campa &amp; Ind. (Dynae)</td>
<td>Artemis</td>
</tr>
<tr>
<td>2</td>
<td>CityMap</td>
<td>A. Farina – University Parma</td>
</tr>
<tr>
<td>3</td>
<td>DataKustik GmbH</td>
<td>Cadna A</td>
</tr>
<tr>
<td>4</td>
<td>Eliza</td>
<td>Matec</td>
</tr>
<tr>
<td>5</td>
<td>IMM</td>
<td>Wölfl Mess-Systeme, Software GmbH and Hochberg bei Wurzburg</td>
</tr>
<tr>
<td>6</td>
<td>Impact</td>
<td>Laboratoire d’Acoustique Université Laval, Québec - Canada</td>
</tr>
<tr>
<td>7</td>
<td>Iso 9613 – ½</td>
<td>Belgium research</td>
</tr>
<tr>
<td>8</td>
<td>LIMA</td>
<td>Stapelfeldt Ingenieurgesellschaft mbH</td>
</tr>
<tr>
<td>9</td>
<td>LIMA Light</td>
<td>Stapelfeldt Ingenieurgesellschaft mbH</td>
</tr>
<tr>
<td>10</td>
<td>Mathas</td>
<td>016B</td>
</tr>
<tr>
<td>11</td>
<td>NMPB – Rutes-96</td>
<td>CETUR CSTM LCPC SETRA</td>
</tr>
<tr>
<td>12</td>
<td>Predictor</td>
<td>D.G.M.R. Consulting Engineers</td>
</tr>
<tr>
<td>13</td>
<td>Saul H Lima</td>
<td>Stapelfeldt Ingenieurgesellschaft mbH</td>
</tr>
<tr>
<td>14</td>
<td>SoundPlan</td>
<td>Braustein and Berndt</td>
</tr>
<tr>
<td>15</td>
<td>SPM9613</td>
<td>Power Acoustic Inc.</td>
</tr>
<tr>
<td>16</td>
<td>TNM</td>
<td>FHWA</td>
</tr>
</tbody>
</table>

For each of the listed models a specific analysis has been conducted concerning the section for input data and the schematic of the source [3] [12].

### 3 Operational phases

Three operative macro-phases based on the definition of the characteristics influencing the sound level have been defined.

Figure 2 describes the operational phases necessary to develop the prediction model.

![Fig. 2 - Flowchart of the operative phases](image)

The following characteristics have been registered for the implementation of the model:
- hourly traffic flows and distribution throughout the day,
- vehicular flow characteristics.

Specifically, model data input are relating to the characteristics of the road, the traffic flow and the territorial context determining the sound power value and the sound power value with the presence of attenuators.

In the following phase a campaign of monitoring of noise emissions in the local context of Crotone has been carried out.

The sampling time (UNI, 2005[40]) has been implemented by the division of territory in elementary acoustically homogeneous areas, choosing the numerosness of each sample according to the width of the zone, the flow and the composition of the vehicular current for periods of time significantly large. The duration of this period has been proportionated to the objectives of the survey and to changes in factors that influence the environmental noise.

Once data on the monitoring campaign have been known, a specific integrated prediction model, which contains land use variables and traffic flow variables has been developed.

### 3.1 The mathematical model

To assess the reliability of the forecasting model and to confirm the reliability of the simulated data, a calibration has been made using the experimental findings obtained in the survey carried out in the urban area of Crotone in 2012.

The photometric measurements performed were considered valid because the calibrations before and after each measuring cycle have presented very different below the maximum allowed of 0.5 dB.

All instruments used for the measures were properly controlled in a laboratory accredited by a national calibration service, in accordance with the law August 11, 1991, n. 273, and are therefore provided with a calibration certificate with a date earlier than two years, that certify compliance with technical specifications.

The criteria and conditions under which such measures are set forth in Annex B to the Ministerial Decree. In particular, before the measures it was essential to acquire all the information about the reference and the characteristics of the road and the urban context. The noise measurements have given the variation both for the noise sources and of their propagation. Were detected all the data that have allowed to lead to the description of environmental
noise sources that affect the areas concerned by the survey.

The microphone, mounted on a support and connected to the sound level meter with a cable long enough to allow traders to place themselves at a distance not less than 3 m from it, was oriented toward the source of noise: in this case the direction of traffic vehicle.

The model data relate to two macro-characteristics that influence the $\text{Leq}$ and are the geometric ones and the vehicular traffic data, specifically considering the rate of heavy vehicles.

The geometrical characteristics studied are:
- type of road;
- specifications and design of the road;
- distance of the source;
- The characteristics of the traffic flow detected are:
  - vehicular flow;
  - percentage of heavy vehicles.

In particular, a phonometric system "BRUEL & KJAER mod. 2260, Class 1, defined according to the specifications and EN-60651/1994 EN-60804/1994" has been used to detect levels equivalent.

In Table 2 the characteristics registered during the survey:

<table>
<thead>
<tr>
<th>Macro-characteristics</th>
<th>Characteristics</th>
<th>$RT$</th>
<th>$L_{road}$</th>
<th>$d$</th>
<th>$V$</th>
<th>$V$</th>
<th>$HDT$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Type of road</td>
<td>$L_{road}$</td>
<td>Road section width</td>
<td>$d$</td>
<td>Distance of source</td>
<td>Traffic flow in daytime end hours</td>
<td>$v$</td>
</tr>
</tbody>
</table>

Figure 3 shows how the residuals are distributed normally respecting one of the basic hypothesis for the estimation of model parameters.

Below is the specification of the prediction model and the calibration results:

$$\text{Leq}(V, HDT, d) = \beta_1 \cdot \log(V) + \beta_2 \cdot \log \left( \frac{HDT \cdot V}{100} \right) + \beta_3 \cdot d$$  \hspace{1cm} (1)

$b_1 = 9.339484$

$b_2 = 0.983618$

$b_3 = -0.342838$

$R^2 = 0.69412294$

The model specified above shows how the factor that most influences the $\text{Leq}$ is the vehicular flow $V$ and the percentage of heavy vehicles $HDT$. The distance of the receptor from the linear source, however, affect in an manner inversely proportional to the distance $d$.

3.2 The comparison between the simulated values and the observed values

Table 3 shows the results of a statistical test at a significance level of $\alpha = 0.05$.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_1$</td>
<td>9.339484</td>
<td>0.194479</td>
<td>48.0231</td>
<td>0.000000</td>
<td>8.957058</td>
<td>9.721910</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>0.983618</td>
<td>0.278099</td>
<td>3.5369</td>
<td>0.000456</td>
<td>0.436760</td>
<td>1.530476</td>
</tr>
<tr>
<td>$\beta_3$</td>
<td>-0.342838</td>
<td>0.017578</td>
<td>-19.5039</td>
<td>0.000000</td>
<td>-0.377404</td>
<td>-0.308273</td>
</tr>
</tbody>
</table>

Level of confidence 95% ($\alpha = 0.050$)

The Figures 4 show the comparison between equivalent level estimated by the model and the residues with the respective values obtained from the model.

4 Conclusion
The model developed and presented in this paper starts from a modeling base previously defined and validated through a survey campaign by the same research group ([3], [12]). The regression model simulates, with statistically reliable results, the equivalent level \( \text{Leq} (V, \text{HDT}, d) \) through three specific variables: flow \( V \), percentage of heavy vehicles, \( \text{HDT} \), and the distance \( d \) of the linear source of sound. Obviously the model thus constructed will be verified when applied to different situations from that in which it was developed. Future developments will aim to evolve the model, whereas the special boundary conditions that change the patterns of sound propagation and the specific values of noise levels.

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