A Vehicle Noise Specific Power Concept

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Abstract— The main purpose of this work is to develop a single vehicle noise emission model that uses speed as input variable and returns as output a parameter directly referable to the noise source, namely the source sound power level (Lw). The model was tested on three light-duty vehicles with different motorizations: diesel, gasoline and gasoline-electric hybrid. Field measurements were conducted on a straight road and for different speed values (10-90 km/h). The influence of the engaged gear on the noise at different constant speed values was also explored for gasoline and diesel vehicles using one-way analysis of variance (ANOVA). Results revealed that the source power level emitted by different typologies of cars against speed followed significantly different trends, more evident at speeds lower than 40 km/h. In such cases, the contribution of the engine on the noise is prevalent and ANOVA test confirmed that the gear choice influenced the noise at low speeds. At higher speed values such difference disappears.

Keywords: noise measurements, noise models, vehicle specific power.

I. Introduction

Long exposure to road traffic noise, even in the night hours, could affect the human well-being as means of potential health problems [1], [2], such as morning tiredness, hearing problems, sleep disorders [3] and cardiovascular complications [4]. Moreover, noise is the second most significant environmental problem, immediately after air pollution [5].

The noise produced by a vehicle is associated to the engine and rolling (contact between the tyres and asphalt) contributions [6]. Despite all the improvements in both car and tyres manufacturers that allowed to reduce significantly the noise produced by vehicles, it is estimated that approximately 75 million of people in Europe are exposed to day-evening-night noise level (L_{den}) caused by road traffic exceeding 55 dBA, while around 55 million of people are exposed to night noise levels exceeding 50 dBA, and these numbers are expected to rise in the next years [7].

The expected growth of road traffic volumes in Europe leads to an increase of traffic-related noise and social costs [8]. The European Union (EU) is committed in gathering efforts to reduce the noise traffic and enacted the directive 2002/49/CE that relies on three main aspects: (i) to create noise maps through the use of a common assessment to the member states; (ii) to ensure that noise information and its effects are made available to the public; and (iii) to adopt action plans based upon noise-mapping results in order to inform the population on the effect of noise pollution and reduce it in the critical area. Monitoring road traffic noise includes noise measurements and often requests costly equipment and significant number of human resources. For this reason, the development of models is useful to evaluate the impact of noise produced by road traffic.

It is worth mentioning that most of existing noise models give as output the equivalent continuous sound pressure level (L_{eq}) produced by the traffic flow in a certain time. Some of these models estimate the source power level (L_w) of the flow, starting from the single vehicle noise emission. L_{eq} represents the average energy of the fluctuating sound level, as follows:

$$L_{eq} = 10\,\mathrm{Log}\left[\frac{1}{\Delta t}\int_{t_1}^{t_2}\frac{p^2}{p_0^2}\,dt\right], \tag{1}$$

where: Δt is the time to which L_{eq} refers; p the sound pressure in Pa; and p_0 is the reference pressure equal to 20 μPa.

As well as other important noise parameter, including sound pressure level (L_p) and percentile levels, L_{eq} also depends on noise propagation. This requires an additional parameter as the distance between the noise sources and the receiver. Usually, for single vehicles, the point source propagation formula is adopted [6].

L_w can be defined as:

$$L_w = 10\,\mathrm{Log}\frac{W}{W_0}, \tag{2}$$

where: W is the sound power in Nm/s and W_0 is the reference sound power equal to 10^{-12} Nm/s.

Since L_w is a characteristic of the noise source, i.e., a vehicle, this means that it is an invariant quantity with the source-receiver distance. It depends on several parameters such as vehicle speed, acceleration and jerk (the time derivative of acceleration), engine load (the combination of the revolution per minute – RPM and the gear engaged), road slope, type of tyres, road surface, etc.

Moreover, several models provide a differentiation for different vehicle classes, for instance light and heavy-duty vehicles, proposing same or similar formulas to estimate the relative noise emission levels.

As mentioned previously, noise produced by a vehicle has two main contributions: engine and rolling. For speeds under 40 km/h, the contribution of the engine is prevalent, and the noise is more affected by variables such as RPM, engaged gear, acceleration; for higher speeds, the rolling part (contact between tyres and road surface) is predominant and noise is less influenced by the above-mentioned parameters [6].

As it happens for pollutant emissions, a noise model without a proper diversification of vehicles category may produce inaccurate estimates. This is especially true in low speeds, in which the contribution of engine is higher. In fact, pollutant emissions produced by vehicles are directly related to the vehicle specific power (VSP) [9]. VSP is a function of vehicle speed and acceleration, and road grade (slope) on a second-by-second basis. It allows to estimate emission factors for different pollutants (carbon dioxide, carbon monoxide, nitrogen oxides and hydrocarbons) in different types of vehicles and propulsion technologies, such as passenger gasoline [10], diesel [11] and hybrid electric [12], light commercial diesel vehicles [11] and diesel transit buses [13]. Additionally, recent studies showed emissions can be also estimated using internally observable variables such as RPM and manifold pressure [14], [15]. Following these approaches, one might think that the same can occur regarding noise emission estimation. For instance, if a passenger car is considered, then noise would be accounted for a generic category of vehicles. However, if there are different propulsion types (i.e., gasoline, diesel, hybrid or electric engine), then noise may be different under same dynamic conditions.

Therefore, the main purpose of this work is to pave the way to a single vehicle noise emission model, called Vehicle Noise Specific Power (VNSP) Model, that, following the idea behind the VSP methodology, gives as output the source sound power level, L_w, for multiple categories of vehicles based on their motorization, taking into account the speed. This work also explores the influence of gear choice at a certain speed on the noise using one-way analysis of variance (ANOVA) test. The single vehicle noise emission level estimation can be used to assess the overall road traffic noise, by summing the contributions of each vehicle included in the traffic flow. The developed model can be incorporated in an Intelligent Transport System (ITS) tool that allows traffic planners and local authorities to assess traffic-related noise hotspots and to support noise-oriented policies considering the car fleet characteristics.

II. Literature review

Many models have been developed in the scientific community to assess road traffic noise, using several different approaches, some of them estimating the single vehicle source power level. Quartieri et. al [16] developed a noise model that estimates the noise emission of the traffic flow, considering empirical formulas, and then computes the L_{eq}^{1h} using the hourly flow of light and heavy-duty vehicles (respectively Q_L, Q_H) and the distance between the noise sources and the receiver (d). Also, they incorporate a parameter regarding the number of light-duty vehicles that produce the same acoustic energy of a heavy one (n) and, the average speed of traffic flow. ASJ-RNT noise traffic model [17] estimates L_w for three categories of vehicles namely, light, heavy-duty and motorcycles, using their speed as input variable. A correction term that includes the type of road surface, the slope and the directivity factor is considered. Different equations are used depending on driving state, namely steady-state conditions, acceleration and deceleration phases. SonRoad model [18] estimates L_w for two categories of vehicles, namely light and heavy-duty vehicles, knowing their speed; this model includes correction terms for road surface and road gradient. FHWA is a traffic noise model developed by the Federal Highway Administration [19], which computes the vehicle noise emission level (E_A) for five categories of vehicles (automobiles, medium trucks, heavy trucks, buses and motorcycles) based on their speed; a correction term for driving condition (full throttle or steady-state situation) is considered. NMPB noise model [20] is based in a quite different approach: it splits the effect of engine and rolling noise, computing respectively, $L_{w,engine}$ and $L_{w,rolling}$ for two categories of vehicles (passenger and heavy-duty); for the rolling piece, the model proposes different formula for three types of road surfaces, while for the engine component it uses different coefficients according to the driving conditions (acceleration and deceleration phases). The CNOSSOS model [6] was developed to create the noise maps imposed by the directive 2002/49/CE; it derives from Harmonoise [21] and Imagine [22] models, sharing the shapes of equations. It estimates L_w for each band of octave, from 125 Hz to 4 kHz, for four categories of vehicles: light motor, medium-heavy, heavy and powered two-wheelers, dividing the effect of engine and rolling. Several correction terms are developed to account the effects on the noise of studded tyres, air temperature, road gradient, acceleration and deceleration phases, type of road surface or the proximity to an intersection.

While there has been extensive research focusing on the development of noise models based on vehicle activity data, the quantification of noise using different motorization types is scarce. The above studies did not explore in detail the effect of different gears on noise, which is one of the objectives of this research. In what follows, the suggested approach of the VNSP is described and then, tested for passenger cars of different fuel types on a hilly road and with different speed values. For both gasoline and diesel vehicles, different combinations of speed and gear were used.

III. Methodology

Fig. 1 summarizes the methodology used to conduct this study.

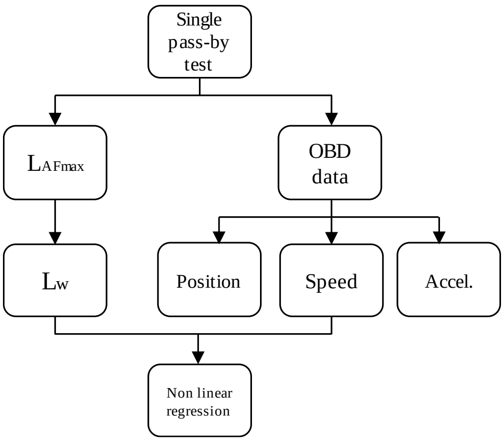

Figure 1. Description of the global methodology in noise specific model

A. Experimental Design and Instruments

Noise and vehicle dynamic data were collected. In particular, several single pass-by tests were performed at constant speed to estimate L_w produced by the vehicle. Three different passenger cars were used and their main characteristics are summarized in TABLE I. Each vehicle was equipped with an OBD-II ELM 327 with Bluetooth connection to record second-by-second On-Board Diagnostics data (OBD), such as speed and RPM.

TABLE I. MAIN CHARACTERISTICS OF PASSENGER CARS USED

Type of fuel	Diesel	Gasoline	Hybrid Electric Gasoline
Transmission type	5 speed manual	5 speed manual	automatic
Gross vehicle weight	1,200 kg	1,590 kg	1,860 kg
Engine Size	1.2 L	1.2 L	1.8 L
Number of cylinders	4	3	4
Tyres width	185 mm	195 mm	215 mm
Tyres aspect ratio	65	60	60
Tyres diameter	15 inches	16 inches	17 inches
Model year	2017	2017	2019

To record noise data, a class 1 sound level meter was used (RION-NL-52). Before measurements, the instrument was properly calibrated using a reference signal of 94 dB at 1000 Hz. A-weighted curve and Fast time constant (125 ms) were used. The clocks of the sound level meter and of the smartphone connected to the OBD were also synchronized. It must be also mentioned that tyres pressure was previously checked.

Single pass-byes tests should be conducted in a street with negligible traffic volumes and background noise as well. Absence of buildings and barriers nearby is preferable in order to avoid noise reflections. Moreover, street length should be sufficient to reach high speed in safety conditions and road pavement should be regular as much as possible. For these reasons, a street on the outskirts of Aveiro (Portugal) was considered for this study. It gathers the following characteristics: street length is about 0.5 km, street grade is approximately 6%, one-way direction with two lanes, and width of 5.5 m.

The driver was asked to maintain a constant speed, following the centerline of the lane road without change gear, at least 150 m before and after car passing in front of the sound level meter. For all tests, the sound level meter was set on tripod at 1.2 m of distance from the ground. The distance between the instrument and the centerline of the lane road used to measure L_{Amax} can be chosen arbitrary, in fact values equal to 7.5, 15 and 25 m was set respectively in SonRoad, FHWA and RLS90 models ([18], [19] and [23]). Although the choice of short distances allows to reduce noise reflections effects, the point source approximation of the vehicle could be compromised. In this study, a distance of 15 m was set.

A total of 115, 112 and 111 valid single pass-by tests were conducted respectively for diesel, gasoline and hybrid car. TABLE II presents all the combinations of speed and gear obtained. It is worth noting that the hybrid vehicle does not allow to control the gear engaged, hence during the tests the speed was the only parameter considered. All measurements were conducted in sunny days from October to December 2019, with wind speeds lower than 5 m/s, ambient temperature ranging from 11°C to 17 °C and humidity from 64% to 88%. The background noise was checked before each measurement, and the test was considered valid only if environmental noise was at least 10 dBA lower than maximum A-weighted sound pressure level (L_{Amax}) of the pass-by, and if no external cause of noise appeared (such as for instance sound of bells, other vehicles on the road, or dogs barking).

TABLE II. TESTS' PARAMETERS

Speed [km/h]	Gear used	Average RPM Diesel car	Average RPM Gasoline car
10	1st	1240	1360
15	1st, 2nd	1850, 1030	2225, 1250
20	1st, 2nd	2360, 1280	2820, 1590
25	2nd	1570	1865
30	2nd, 3rd	1815, 1200	2130, 1600
35	2nd, 3rd	2120, 1410	2670, 1880
40	2nd, 3rd	2335, 1505	2850, 2000
50	3rd, 4th	1920, 1405	2665, 2035
60	3rd, 4th	2300, 1670	3215, 2425
70	3rd, 4th, 5th	2700, 1930,	3580, 2715, 2190
80	4th, 5th	2220, 1610	3120, 2530
90	4th, 5th	2590, 1900	3710, 2810

B. Data analysis

The raw noise and OBD data of each run were treated in order to obtain L_{Amax} and the speed corresponding to the instant when the vehicle passed right in front of the sound level meter. Since cruise speed control was not available for speed values under 40 km/h, the speed information displayed by OBD was used as a reference for driver, since the vehicle tachymeter is not precise enough and tends to overestimate the speed.

L_w was computed using the noise propagation formula provided in [24], as follows:

$$L_w = L_{Amax} + 20\,\mathrm{Log}(d) + 11. \tag{3}$$

It must be stressed that 11 is equal to 10 Log(4π) and represents a spherical propagation (i.e., pointlike source) and a pavement completely absorbent.

The approach proposed here to obtain L_w is based on CNOSSOS [6] model functions with some differences. In fact, CNOSSOS computes L_w for each band of octave, from 125 Hz to 4 kHz, dividing the effect of propulsion ($L_{w,propulsion}$) and rolling ($L_{w,rolling}$). Therefore, the mathematical equations of $L_{w,propulsion}$ and $L_{w,rolling}$ are given by Equations 4 and 5, respectively:

$$L_{w,i,m,propulsion} = a_{i,m} + b_{i,m}\,\frac{v - v_{ref}}{v_{ref}}, \tag{4}$$

$$L_{w,i,m,rolling} = c_{i,m} + d_{i,m}\,\mathrm{Log}\left(\frac{v}{v_{ref}}\right), \tag{5}$$

where: a, b, c and d are coefficients given for each category of vehicles (m) and for each band of octave (i), v is the speed of the vehicle in km/h, and v_{ref} is the reference speed equal to 70 km/h.

The overall source power level of a vehicle is given by the logarithmic sum of the $L_{w,propulsion}$ and $L_{w,rolling}$ contributions:

$$L_w = L_{w,\text{propulsion}} \oplus L_{w,\text{rolling}}, \tag{6}$$

Here, the purpose is to fit the values of L_W obtained with eq. 3, through a non-linear regression, using the following single formula:

$$L_w = 10\,\mathrm{Log}\left[10^{0.1\left(A+B\frac{v-v_{ref}}{v_{ref}}\right)} + 10^{0.1\left[C+D\,\mathrm{Log}\left(\frac{v}{v_{ref}}\right)\right]}\right]. \tag{7}$$

L_W and v will be the dependent and independent variables of the regression respectively, while A, B, C and D represent the coefficients to be estimated. It must be stressed that, these coefficients are provided for the total sound power level and not for each band of octave as in CNOSSOS. A Matlab® routine was conceived to compute the coefficients using an iterative method minimizing the least squares, providing attempted value.

IV. Results

The results obtained for diesel, gasoline and hybrid cars are shown in this section. The regression models are presented, followed by the ANOVA test of gear effect on noise.

A. Regression function

The L_W values estimated with constant speed pass-byes for each speed/gear combination were used to compute the coefficients of eq. 7 with a non-linear regression.

The regression and determination coefficients are shown in TABLE III. It must be stressed that coefficient B obtained for the hybrid car has negative sign, in contrast to the other cases. This can be explained with the fact that the VNSP does not take into account the car-operating mode. This type of vehicle, in fact, works differently in relation to conventional ones. At low speeds, only the electric engine contributes to the motion of the vehicle and, if the battery level is not high enough, the internal combustion engine turns on to recharge them. Moreover, at high speeds the electric part contributes to the motion of the vehicle, subtracting load to the internal combustion engine.

TABLE III. REGRESSION RESULTS

Car	A	B	C	D	R^2
Diesel	98.77	15.28	102.76	35.74	0.94
Gasoline	98.02	17.61	105.06	31.08	0.98
Hybrid	22.06	-65.81	104.44	34.25	0.99

Bearing in mind (4), (5) and (7), it is possible to note that there is a linear dependence between L_W and speed for engine noise contribution, while it turns into a logarithmic dependence for rolling part. In fact, this can be seen in the regression functions presented in Fig. 2, confirming that, for all vehicles, they follow a straight-line changing course into a logarithmic function for speeds higher than 40 km/h. This fact confirms the prevalence of engine noise contribution on L_W at low speeds and a stronger contribution of rolling noise at higher ones.

The regression functions show a different trend in lower speeds, which may be attributed to different engines typologies that significantly affect the noise in this range of speeds. For instance, Fig. 2-c suggests constant noise values for speeds between 10 and 15 km/h. This happened because hybrid vehicle is operating at electric mode only at those range of speeds. The plots in Fig. 2a and 2b show that the variability in noise values was particularly substantial for speed values of 15 km/h and 20 km/h. This could suggest an impact of gear for those speed values.

For a speed range from 10 to 40 km/h, the slope of the regression function for diesel vehicle is smoother than gasoline. This may be due to the fact that a diesel engine produces more torque than a gasoline engine at low RPM values, which becomes more relevant on a hilly road. The source power levels for hybrid car were below the other cars, inasmuch for low speed the electric part strongly helps the internal combustion engine in the propulsion, thus resulting in reduction in noise.

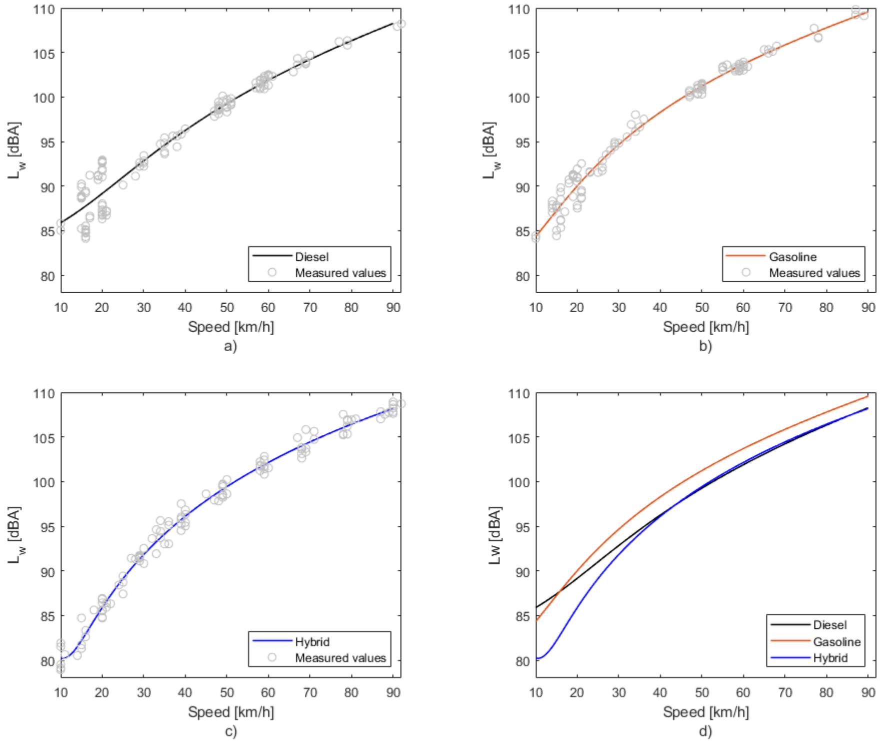

Figure 2. Regression functions for a) diesel, b) gasoline, c) hybrid and d) comparison among vehicles

B. ANOVA test

This section presents the ANOVA results concerning the influence of gear choice on the noise in a constant speed run for diesel and gasoline vehicles. As mentioned before, 15 and 20 km/h yielded substantial variations in noise values in gasoline and diesel vehicles. Thus, four values of speed (15, 20, 50 and 60 km/h) and corresponding gear (see TABLE II for details) were selected to assess the gear contribution on the noise level for a specific speed value. Several pass-by runs were executed for each selected speed/gear combination and then, the L_w values were estimated from (3).

TABLE IV shows the ANOVA results. It was found that

in both diesel and gasoline vehicles, F value (i.e., ratio between the variance of the sample means and the mean of the within samples variance) is higher than $F_{critical}$ in lower speeds (15 and 20 km/h). The ANOVA results for 50 and 60 km/h did not follow the same trend. This suggests that the choice of the gear affects the noise levels in low speeds regime, while it is almost irrelevant for higher ones. In fact, choosing a gear instead of another leads to a different engine load, thus, its effect on noise could be more evident in the low speeds range where, as mentioned, engine noise contribution is stronger.

TABLE IV. ANOVA TEST RESULTS

Car	Speed [km/h]	Gear ratio	Gear ratios	Sample size	Average [dBA]	Variance	F	F_{crit}	p-value
Diesel	15	1st	3.91:1	10	89.38	0.71	127.99	4.41	1.300E-9
		2nd	2.16:1	10	85.19	0.66			
	20	1st	3.91:1	10	91.79	0.63	241.86	4.41	7.030E-12
		2nd	2.16:1	10	87.11	0.26			
	50	3rd	1.48:1	10	98.68	0.22	4.30	4.41	0.052
		4th	1.12:1	10	99.20	0.41			
	60	3rd	1.48:1	9	101.52	0.22	1.54	4.49	0.232
		4th	1.12:1	9	101.82	0.30			
Gasoline	15	1st	3.42:1	7	88.44	0.75	31.46	4.74	1.114E-4
		2nd	1.80:1	7	85.78	0.82			
	20	1st	3.42:1	10	91.21	0.38	46.32	4.41	2.260E-6
		2nd	1.80:1	10	88.92	0.75			
	50	3rd	1.28:1	9	100.78	0.20	0.15	4.49	0.699
		4th	0.98:1	9	100.87	0.25			
	60	3rd	1.28:1	10	103.43	0.07	2.48	4.41	0.151
		4th	0.98:1	10	103.24	0.09			

V. Conclusions

In this paper, a new approach for estimating single vehicle noise emission was proposed. The work contributes to the existing literature on noise emission models by providing a classification based on vehicle motorization (diesel, gasoline, hybrid). The results obtained are promising and suggest that noise estimation of vehicles accounting for their motorization is useful for an accurate estimation. In particular, the results obtained with the hybrid vehicle highlight the much lower noise emission in the low speeds range. Therefore, a strong differentiation between the vehicles belonging to the same category should be considered in order to obtain robust noise models. It was also concluded that the choice of gear in low speeds affects noise emitted by gasoline and diesel vehicles.

The small sample size of the fleet tested does not allow to generalize the obtained regression functions for all diesel, gasoline and hybrid vehicles; it suggests that noise estimates can be obtained for vehicles with similar technology and engine size. The proposed methodology can be easily replicated on other vehicles types (namely, electric passenger cars, vans, motorcycles, heavy-duty vehicles). Thus, future research involves the improvement of the proposed methodology by including more typologies of vehicles and by implementing other input parameters, such as acceleration, vehicular jerk and/or road gradient. Moreover, the impact of type of tyres on noise should be also explored. This would be a main step for the development of an innovative Vehicle Noise Specific Power model (VNSP), similarly to the Vehicle Specific Power (VSP) used for pollutants.

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