



Effect of Load on Engine Noise for the Auralization of Road Traffic

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Summary

Previous work has shown the benefit of assessing urban noise exposure through perceptual evaluations. This explains the increased interest in auralization techniques applied to urban soundscape. Recently, a new approach for the real time synthesis of vehicle noise with varying speed was developed and implemented in an outdoor noise auralization framework. Coupled to a dynamic traffic model which considers vehicles individually, the approach is able to precisely auralize noise exposure at crossings with stop lights or roundabouts for instance. In this approach, the noise emission level of each vehicle is calibrated such as to follow the Harmonoise model. However, the effect of engine load on noise emission was so far neglected, which underestimates noise exposure in presence of vehicles with high acceleration levels. This paper presents recent progress to efficiently implement the effect of engine load. Measurements were carried out to characterize the load and its influence on noise emission for a number of vehicles. Based on this data, a simplified model is proposed to apply the effect of load on the synthesized engine signals. Results compare the emission levels obtained on auralized sequences of accelerating vehicles with existing models based on experimentally measured pass-by noise levels.

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1. Introduction

Auralization of traffic noise has been a research subject of increasing interest in recent years. The progress accomplished in this field provides tools for the perceptive evaluation of noise exposure in environments where listening tests based on audio recordings are not practical. These tools are based on existing predictive models which they efficiently complement by allowing the evaluation of noise pollution based on perception. Indeed, noise level exposures can be difficult to translate into annoyance levels. The subjective evaluation of soundscapes is therefore important for an accurate assessment of comfort or annoyance.

Most of the previous work on road noise auralization assumes stationary traffic conditions with constant vehicle speeds. In these studies, vehicle source signals are obtained from pass-by audio recordings of individual vehicles [1, 2, 3]. Recently, a new approach was proposed for the real time synthesis of engine noise with varying engine speed [4]. A similar approach was also applied to rolling noise [5, 6]. The ability to synthesize vehicle noise for time varying speeds now enables the auralization of non-stationary traffic including accelerating and decelerating vehicles.

The approach referenced above uses calibrated engine noise synthesis following the Harmonoise emission model [7]. This model represents averaged emission levels from vehicle pass-by measurements and therefore includes the effect of engine load on radiated noise levels. However, this effect is averaged as a global calibration gain which is applied to the synthesized engine noise. In other words, engine load is not rendered dynamically based on vehicle operating parameters such as speed, acceleration, gear or road slope. It is however clearly established that varying engine load has a non-negligible effect on radiated noise [8, 9]. Depending on the load, an internal combustion engine requires different amount of fuel to reach a given rotational speed. As the amount of fuel inside the cylinders directly affects the pressure pattern due to the combustion process, it also affects the noise radiated by the engine.

This paper proposes a modified auralization framework for traffic noise including the effect of engine load induced by current vehicle operating parameters such as speed, acceleration, gear and road slope. The approach enables audio rendering of the effect of engine load and thus improves the accuracy of the auralization output in cases where engine load variation has a

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significant influence on the overall radiated noise. Urban road crossing with stop lights and heavy traffic is an example of such cases.

The paper first presents a method to estimate engine load from vehicle operating parameters. The characterization of the effect of load on radiated noise for a given engine is then discussed, followed by a presentation of the implementation within the existing auralization framework. The last section presents results comparing the emission levels obtained with the proposed approach with the Harmonoise emission model for various engine load configurations, including dynamic load variations.

2. Engine load estimation

The load of an engine is proportional to a pressure quantity, \mathcal{B}_p , the Brake Mean Effective Pressure (BMEP) [10]. It is defined as the average pressure which, if imposed on the pistons uniformly from the top to the bottom of each stroke, would produce a given torque at the output of the engine. At full load, \mathcal{B}_p is maximal and the engine outputs its maximal torque. The maximum BMEP of an engine is a relative measure of the engine performance independent of the engine size. The BMEP is obtained by dividing the work per engine cycle by the cylinder volume displaced per engine cycle [11]. This is expressed as

$$\mathcal{B}_p = \frac{N_c}{2} \frac{60P_b}{rpmV_d} \qquad [Pa] \tag{1}$$

where P_b is the brake power, i.e. the power that is transmitted to the flywheel of the engine, N_c is the number of cylinders of the four stroke engine, rpm is the engine rotational speed and V_d is the cylinder volume displacement. The BMEP can also be expressed as a function of brake torque T_b which represents the torque transmitted to the flywheel of the engine:

$$\mathcal{B}_p = \frac{\pi N_c T_b}{V_d} \qquad [Pa] \tag{2}$$

Engine load may be defined as the BMEP value [10] or more commonly as the ratio in percent between the BMEP and the maximum BMEP [12]. In the latter case, full load is associated with a 100 % load value and no load, with 0 %. The maximum BMEP, \mathcal{B}_p^{max} , can be estimated from vehicle manufacturer data using the maximum torque of the engine.

The following now discusses the estimation of engine load for a moving vehicle. As shown above, engine load is related to the brake torque applied to the engine flywheel. The brake torque can be estimated from the vehicle characteristics (weight, drag coefficient, frontal area, transmission loss) and current values of speed, acceleration and road slope.

First, the forces applied to the vehicle in motion must be estimated. There are three main resistive forces opposed to the propulsion force of the engine [13].

The friction force represents the force applied by the road surface on the tires. It is induced by the tire deformation at the contact between tires and road surface. Its modulus can be expressed as

$$|\mathbf{F}_{\mathbf{friction}}| = mgC_r \qquad [N] \tag{3}$$

where m is the vehicle weight in kg, g is the acceleration due to gravity ($g = 9.81 \text{ m.s}^{-2}$) and C_r is a dimensionless coefficient depending on tire and road surface type. It generally varies between 0.005 and 0.015. A middle value, $C_r = 0.010$, is generally accepted as a good average for standard light vehicles on asphalt concrete roads.

The air resistance (or drag force) stands for the effect of air on the vehicle body. Its modulus is expressed as

$$|\mathbf{F}_{air}| = \frac{1}{2}\rho v^2 S_x C_x \qquad [N] \tag{4}$$

where ρ is the air density ($\rho = 1.2 \text{ kg.m}^{-3}$), v is the vehicle speed in m.s⁻¹, S_x is the vehicle frontal area in m² and C_x is the drag coefficient (both provided by vehicle manufacturer).

The force due to vehicle weight, gravity and road slope is expressed as

$$|\mathbf{F}_{slope}| = mg\sin\alpha \qquad [N] \tag{5}$$

where α is the road slope in radians.

The vehicle must output a propulsion force $\mathbf{F}_{\mathbf{prop}}$ to counter the three resistive forces listed above and produce an acceleration a, positive when it accelerates the vehicle, negative otherwise:

$$|\mathbf{F}_{\mathbf{prop}}| = ma + |\mathbf{F}_{\mathbf{friction}}| + |\mathbf{F}_{\mathbf{air}}| + |\mathbf{F}_{\mathbf{slope}}|(6)$$

The transmission loss between the engine output torque and the torque delivered to the vehicle wheels through a manual transmission and a front wheel drivetrain is approximately 15 % which yields a transmission efficiency $\eta = 0.85$. Now considering the gearbox and axle ratios and the wheel diameter, the brake torque of the engine necessary to achieve a propulsion force $|\mathbf{F}_{prop}|$ is expressed as

$$T_b = \frac{T_{wheel}}{r_{gear_i} r_{axle} \eta} = \frac{R_{wheel} |\mathbf{F}_{\mathbf{prop}}|}{r_{gear_i} r_{axle} \eta} \tag{7}$$

where r_{gear_i} is the gearbox ratio corresponding to gear i, r_{axle} is the axle ratio and R_{wheel} is the wheel radius.

Replacing Eq. 6 and 7 in Eq. 2, the Brake Mean Effective Pressure can be written as

$$\mathcal{B}_{p} = \frac{\pi N_{c} R_{wheel}}{\eta r_{gear_{i}} r_{axle} V_{d}} \times \left(mgC_{r} + \frac{1}{2} \rho v^{2} S_{x} C_{x} + mg \sin \alpha + ma \right) \quad (8)$$



Figure 1. Picture of the DPA microphone equipped with wind protection near the engine block of a diesel vehicle.

3. Effect of load on radiated noise

Most recent methods for engine noise measurement make use of roller benches equipped with magnetic brakes to simulate engine load. These are installed in semi-anechoic chambers to reproduce free field conditions. The load applied to the engine can be varied in real time with a control software by setting the torque (in Nm) of the roller bench. For lack of sufficient funding, the use of such facilities has not been considered in this work. Instead, on-board recordings of the engine noise radiated in the engine compartment were performed during vehicle motion under various load conditions. To this purpose, a small microphone (DPA 4060) was installed in the engine compartment as illustrated in Figure 1. In this configuration, rolling and aerodynamic noise do not significantly affect the engine noise measurement.

The effect of load is estimated by comparing, for a given engine speed, the measured noise levels of the engine under a given load with the engine under zero load. As the effect of load on radiated noise is expected to be dependent on engine speed, this must be performed over the entire engine rpm range. Note that the proposed approach assumes that the effect of load on radiated noise inside the engine compartment do not significantly differ from the effect of load on radiated engine noise in the far field.

The driving conditions on a normal road make it difficult to maintain a constant engine load while varying engine speed at a slow rate such as to allow good measurement accuracy. A special protocol was therefore adopted taking advantage of the engine noise granular synthesis technique recently developed at CSTB [4] and already implemented in the auralization framework. In this protocol, recorded signals corresponding to various load conditions and spanning the entire rpm range of an engine are used to construct grain datasets. The load conditions are obtained by varying driving conditions such as road

Table I. Number of rpm ramp-ups recorded for different driving conditions.

	Expected load	Diesel	Gas
No gear engaged	no load	2	2
Slope : 0 %, gear :1	low load	3	3
Slope : 8 %, gear :1	mid load	3	2
Slope : 8 %, gear :2	high load	2	1

slope, acceleration and gear for each recording. The no load configuration is obtained with the vehicle at rest and no gear engaged. Each recorded signal yields a grain dataset. Table I summarizes the number and type of recordings that were carried out with the diesel and the gas engine vehicles. Using the granular synthesis technique, high fidelity engine noise signals of arbitrary duration may then be synthesized for different engine speed values. In practice, the available engine speed range is divided into subsets of 100 rpm width. The effect of load is then determined by synthesizing signals in each rpm subset, estimating the associated load and noise levels.

The overall procedure can be summarized as follows:

- Calculate the engine load variation in each input recording as expressed in Eq. 8. Estimating the signal fundamental frequency [4] yields the engine speed and, in turn, vehicle speed and acceleration using the gear, axle ratio and wheel diameter.
- Grain datasets are generated from each input recording as described in [4].
- For each rpm subset of each dataset, the corresponding engine load is estimated by averaging the estimated load over the segment of the input signal from which the grains were extracted. This process determines (load,rpm) pairs for which the effect of load can be obtained. Figure 2 illustrates the (load,rpm) pairs obtained with this approach for the input signals listed in Table I.
- For each (load,rpm) pair represented in Figure 2, an engine noise corresponding to a ramp-up over [rpm-50 rpm+50] is synthesized and its A-weighted octave band levels estimated.
- The difference between the levels obtained for the loaded and unloaded signals represent the load effect on the engine radiated noise expressed as octave band frequency gains.

Figure 3 presents the A-weighted levels per octave frequency band for two different engine speeds (1500 and 4000 rpm). For the diesel engine, load has a negligible effect on the low frequency range, especially at higher engine speed. The effect of load is more important at lower engine speeds for both types of engine. However, for the diesel engine, the effect of load is mainly perceptible in the higher frequencies while it is predominant in the low frequency range for the gas engine. Overall, loaded engine noise signals have an increased high frequency content for the diesel engine



Figure 2. Distribution of (load,rpm) pairs obtained for diesel (left) and gas engine (right). The colors correspond to the type of recording: (red) no gear engaged, (blue) 0% slope/ 1^{st} gear, (green) 8% slope/ 1^{st} gear and (black) 8% slope/ 2^{nd} gear.



Figure 3. Octave band A-weighted levels of the noise inside the engine compartment for 1500 and 4000 rpm under different engine load conditions for diesel (left) and gas engine (right).

while they have an increased low frequency content for the gas engine. This attests that there are important differences in the effect of load on the noise radiated by different types of engine. Note that this is consistent with results from the literature on the effect of load on engine noise [8, 9].

4. Implementation in the auralization framework

The auralization framework implementing real time engine noise synthesis was presented in previous work [5, 6]. It includes three main components: the road traffic simulator, the vehicle source signal synthesis and the moving source renderer. The traffic simulator calculates the position, speed and acceleration of all vehicles moving on the road network. For each vehicle, the source synthesis module uses the vehicle type, road surface, speed and acceleration to adjust the generation of engine and rolling noise source signals. The source signal synthesis implements a real time granular synthesis technique where sound samples are assembled using a synchronous and asynchronous overlap-and-add algorithm for the engine and rolling noise, respectively [4]. Both engine noise and rolling noise signals are fed to the moving source renderer which implements the signal processing steps necessary to model acoustic propagation along a number of time varying acoustic paths.

An intuitive solution to account for engine load would be to consider engine load as a second control parameter of engine noise synthesis and hence, create datasets of grains from engine noise signals corresponding to different load conditions. This has two main drawbacks. First, recording loaded engine noise signals radiated in the far field can only be performed on a roller bench. The recordings performed in this study inside the engine compartment do not represent the acoustic field radiated by the vehicle in the far field and can only be used to analyze the effect of load. Second, using multiple datasets corresponding to different loads for each engine requires considerable storage capacity and higher computational load for grain selection. Ensuring continuity in variable engine load synthesis without audible artifact when switching from datasets also requires further research.

The solution proposed in this work consists in applying appropriate filtering to the synthesized signal of the engine under zero load to simulate the effect of a given load. The auralization system implements octave band filtering to model the frequency attenuation associated with propagation effects. Therefore, modeling the effect of engine load by filtering the synthesized engine noise signal through the same octave band filter bank does not significantly increase the computational load. Note that octave band equalization is not the optimal method to simulate the effect of load since it will not reproduce precisely the time and frequency modifications of the signal due to the effect of load. However, informal listening tests showed that synthesized signals of noise radiated under no load and filtered in this manner are perceptually close to recorded noise of loaded engine.

The previous section presented a method to estimate the effect of engine load for (load, rpm) pairs by comparing loaded and unload engine signals for a given engine speed. This results in octave band differential gains for a discrete set of (load,rpm) pairs. In order to provide differential load gains for arbitrary load and engine speed values, linear interpolation in the (load,rpm) plane is performed as a pre-calculation step. Figure 4 gives an example of interpolated gains in the 1 kHz octave band for a diesel engine. Recalling the synthesized signal is based on grain datasets obtained from engine noise recordings with no load (the



Figure 4. Interpolated diesel engine load gains for the 1 kHz octave band.

vehicle is at rest with no gear engaged), the engine signal with a given load is obtained by applying the load gains to the synthesized zero load signal.

To determine the load gains for current engine operating parameters, the engine load is first estimated. The estimate is based on Eq. 8 where vehicle speed, acceleration and road slope are provided by the traffic simulator and vehicle characteristics (weight, frontal surface, drag coefficient, etc.) as well as current gear are available during real time processing. The engine load gains are then obtained, based on current load and engine speed, from the lookup table of interpolated load gains.

5. Results

To analyze the effect of load on synthesized engine noise signals, a number of constant engine load configurations is first studied. As mentioned earlier, the engine load gains are applied in the same filter bank of the auralization framework as the frequency gains modeling propagation effects. In order to analyze the effect of load on the engine noise only, the propagation effects are by-passed and the rolling noise disabled. The different load configurations are obtained by using constant values of vehicle speed, gear and road slope. Each set of these three parameters are associated with a fixed load. Four light vehicles are considered: 3 diesel engines and 1 gas engine. For each vehicle, the engine noise levels under different load values are compared. As an example of such comparison, Figure 5 represents the A-weighted octave band levels of 6 synthesized signals for a diesel vehicle moving at a constant speed of 45 km/h in third gear on a road with 5 different slopes between 0 and 12 %. The blue line represents the levels of the synthesized signal without taking into account the engine load. It can be seen that a level increase of almost 5 dB is obtained on the A-weighted level for a load of 74 %. As seen



Figure 5. Octave band SPL (A-weighted values) of synthesized engine noise of vehicle 2 (diesel) for varying road slopes (speed and gear are fixed).



Figure 6. Variation of the instantaneous SPL (LAFeq) and engine load obtained on synthesized engine noise of vehicle 2 (diesel) accelerating from 0 to 95 km/h.

previously for diesel engines, the effect of engine load is more important in the upper frequency range.

Cases with a varying engine load are now discussed. In these cases, the vehicle accelerates from 0 to 95 km/h. The exact speed variation is determined such as to represent a realistic acceleration for the considered vehicle. During the acceleration, engine speed varies following successive gear shifts from first to fifth gear. The instantaneous LAFeq level of the engine signal is estimated over the sequence and plotted versus time along with the engine load. Results are shown in Figure 6 for vehicle 2. The solid blue curve shows the noise level with no load taken into account and the green curve with load effect included. The effect of load is clearly seen for each phase of acceleration associated with the different gears. Also note that the load effect is canceled during gear shift when no gear is engaged and the engine is under zero load.



Figure 7. Sound power level Lw of engine noise versus vehicle speed for synthesized signals at constant speed with (blue) and without (green) engine load. The solid blue and green lines represent the linear regression associated with the set of Lw values. The red line represents the Harmonoise model for light vehicles.

The engine emission level, obtained with and without the proposed approach, is now compared with the Harmonoise model by analyzing the distribution of acoustic power levels versus speed. To this purpose, engine noise is synthesized for a set of constant speed values between 20 and 120 km/h including the effect of engine load for all four vehicles considered in this study. The same set of sequences is then constructed without the effect of load. Results are shown in Figure 7 where the acoustic power emission level associated with each signal is plotted versus vehicle speed. The figure also shows the linear regression curve obtained for the signals with load (blue line) and no load (green line). The additional red line corresponds to the Harmonoise emission model for light vehicles. This figure shows that taking into account the effect of engine load yields a better match between synthesized engine noise levels and the target emission model. The increased slope of the blue curve is consistent with the expected effect of load which induces higher noise levels at higher speed where engine load is increased due to air resistance.

6. Conclusions

This paper first proposed a technique to measure the effect of engine load on radiated noise based on measurements inside the engine compartment of moving vehicles. As already discussed in the literature, measured data shows that engine load has a considerable effect on the noise radiated by both diesel and gas engines. In this method, engine load gains per frequency bands can be estimated for different values of engine load and engine speed. The effect of engine load can then be included in existing traffic noise auralization systems using frequency band equalization of unloaded engine noise signals. Results show that the approach effectively improves the fidelity of engine noise rendering, especially when engine load is high. This is the case for accelerating vehicles after crossings, vehicles driving on steep slopes or vehicles at high speed. In those cases, the proposed approach yields more accurate engine noise levels. Future work will include additional recording campaigns on various vehicles with different engines to gather more data on each engine type. Ideally, performing these recordings on roller benches with electronically controlled applied load should be preferred to avoid load estimation errors. This would also enable a larger set of measured load gains in the (load,rpm) plane thus reducing interpolation errors.

References

- T. Kaczmarek. Road-vehicle simulation for psychoacoustic studies. In ICA 2007, Madrid, Spain, 2007.
- [2] A.a Peplow, J.b Forssén, P.c Lundén, and M.E. Nilsson. Exterior auralization of traffic noise within the listen project. In *Forum Acusticum*. European Acoustics Association, 2011.
- [3] Philipp Grams and Dejan Arsić. Auralization of ambient noise in vehicles. In *Forum Acusticum, Krakow*, *Poland.* European Acoustics Association, 2014.
- [4] Jan Jagla Julien Maillard Nadine Martin. Samplebased engine noise synthesis using an enhanced pitchsynchronous overlap-and-add method. *Journal of* the Acoustical Society of America, 132(5):3098–3108, November 2012.
- Julien Maillard and Jan Jagla. Auralization of nonstationary traffic noise using sample based synthesis
 comparison with pass-by recordings. In Proc. of Internoise 2012, New York City, New York, 2012.
- [6] Julien Maillard and Jan Jagla. Real time auralization of non-stationary traffic noise - quantitative and perceptual validation in an urban street. In Proc. of AIA-DAGA 2013, Merano, 18-21 March 2013.
- [7] Dirk van Maercke and Jerome Defrance. Development of an analytical model for outdoor sound propagation within the harmonoise project. Acta Acustica united with Acustica, 93(2):201–212, 2007.
- [8] I. Hirano, M. Kondo, Y. Uraki, and Y. Asahara. Using multiple regression analysis to estimate the contributions of engine-radiated noise components. *JSAE Review*, 20(3):363 – 368, 1999.
- [9] L. Pruvost. Extraction de bruit de combustion d'un moteur Diesel. Développement et application d'un spectrofiltre. PhD thesis, Institut National des Sciences Appliquées de Lyon, July 2009.
- [10] T. Priede. Origins of automotive vehicle noise. Journal of Sound and Vibration, 15(1):61–73, 1972.
- [11] J. B. Heywood. Internal combustion engine fundamentals. McGraw-Hill New York, 1988.
- [12] T. Priede. The effect of operating parameters on sources of vehicle noise. *Journal of Sound and Vi*bration, 43(2):239 – 252, 1975.
- [13] R. Bosch. Mémento de technologie automobile. Delta Press, 2000.