ACOUSTICS 2012

Evaluation of the acoustical performance and behaviour of a hybrid truck in urban use

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Noise emission of mid-sized trucks operating in urban areas for goods delivery and services (for instance waste collect) is crucial, mainly during night and early morning periods. The development of hybrid vehicles is particularly appropriate to urban use since, besides improvements towards energy consumption and pollutant emission, it may also lead to noise reduction, mainly due to the presence of the electric motor. The French research project GEODE gathered several partners for the development of a mid-sized hybrid truck with optimized energy control. One work package consisted in the evaluation of the environmental performance of the vehicle, as compared to an equivalent conventional engine truck. The present paper presents the acoustical part, based on measurements of the acoustic emission under real use conditions: constant speed, acceleration and braking. It includes standard pass-by 7.5 meter noise levels as well as main source analysis, the latter resulting from near-field microphone array measurements, for each vehicle configuration (reference engine truck, hybrid truck under hybrid use, hybrid truck under electrical use). Noise emission laws of the vehicles and of their main noise sources are determined. The electrical mode introduces an undeniable gain at urban speeds, the residual noise resulting mainly from the drive wheel rolling noise.

1 Introduction

Cities are often confronted to dense road traffic, resulting in reduced users' mobility as well as environmental nuisance (air pollution and noise). Increased day-time delivery duration and access restrictions to city centres incite carriers to deliver goods during night and early morning periods. Noise becomes then a crucial matter in residential areas, particularly in connection with the driving phases, including moving off and arrival. Mid-sized hybrid trucks may be an attractive solution regarding environment issues in cities, all the more if a full electric mode is available [1]. The French research project GEODE (2008-2011) aimed at developing a mid-sized electric hybrid truck with an optimized energy control. One workpackage provided the environmental assessment of the vehicle and compared it with an equivalent conventional engine truck. This paper concerns the acoustical item with the evaluation of the noise emission of the hybrid and the reference engine trucks over a wide range of real driving conditions. The study relies on standard 7.5 meter pass-by noise measurements (CPB), as well as on microphone arrays measurements for the description of the noise sources. The respective influence of speed, driving behaviour (gear selection) and vehicle type (conventional engine truck, hybrid truck under hybrid mode, hybrid truck under electrical mode) are investigated from pass-bys at constant speed, with acceleration or braking.

Sections 2 and 3 describe respectively the vehicles investigated, and the acoustical facilities and procedures implemented in the test. The next sections (4 to 6) assess the noise emission for the whole vehicle and for the main noise source zones.

2 Description of the vehicles

Two mid-sized trucks have been tested. Both are vans based on 4×2 solo rigids of the range Premium Distribution (Renault Trucks) / Volvo FE (Volvo Trucks). They differ mainly in the type of drive train. They are equipped with similar tyres although supplied by distinct tyre manufacturers; for each truck, the tyres are different for the drive axle and the steer axle, but taken from the same range. The trucks are loaded with a mass 50 kg/kW.

2.1 The hybrid truck

The hybrid truck was available from the project GEODE (Fig. 1). No specific acoustic treatment was involved in its development, since the main objective of the project concerned energy control. It is equipped with a parallel hybrid drive train and can be operated either in hybrid mode (both the internal combustion engine (ICE) and the electric motor are used together) or in electrical mode (only the electric motor is used). In hybrid mode, the distribution of power provided by the engine and the motor depends on several parameters, among which the battery charge ; it may thus differ in two pass-bys at the same speed. The truck driver may select a "low noise" driving mode, which uses the sole electric motor as long as the battery is sufficiently charged, with a range of about 1 km. There is no "full ICE" mode.

The automatic gearbox has 12 gear ratios. The usable engine speed ranges from 600 rpm (idling) up to 2300 rpm. The tyres belong to the range Michelin X® Energy™.

Figure 1: Hybrid truck

2.2 The reference vehicle

The second truck is a conventional ICE truck, regarded as the reference vehicle for the noise emission comparisons (Fig. 2). It has the same usable engine speed as the hybrid truck, and its automatic gearbox offers 6 gear ratios. It is equipped with tyres from the range Goodyear Marathon.

Figure 2: Reference conventional ICE truck

3 Experimental procedure

The procedure involves the vehicles driving on a test track in various real use conditions, with acoustic measurement at pass-by in both directions. The road surface is 0/10 asphalt concrete. Several acoustic devices were simultaneously operated, leading to complementary information on the vehicle noise emission. The results presented in this paper involve 7.5 m microphones and a microphone array[1].

3.1 Standard 7.5 metre pass-by measurement

Three microphones separated by 10 m were located along and on one side of the track, a fourth one was located on the opposite side. Each of them was positioned 1.2 metre high and at 7.5 metres from the track centre, in accordance with the standard noise measurements [2][3]. The procedure is similar to the Controlled Pass-by standard [3], extended also to pass-bys with acceleration or braking : in each case, the third-octave and global maximum A-weighted noise levels on each microphone are recorded.

Infrared cells provide information on the vehicle speed in front of each microphone position.

3.2 Microphone array measurement and processing

A 41-microphone cross-array is used for the noise source analysis (Fig. 3). The cross centre is 1.17 metre high. The distance between the array plane and the vehicle side is about 2 metres. Each arm is composed of two nested 13-microphone line arrays, with respective uniform spacing 5 cm and 15 cm. The wider spacing is used from low frequency to third-octave 1250 Hz, the shorter spacing from third-octave 1600 Hz to third-octave 4000 Hz. Global noise levels result from the summation of the third-octaves.

Figure 3: 41-microphone cross-array

The array processing used for each line array is delay-and-sum beamforming for spherical waves [5], including also a correction for the attenuation differences and a Chebyshev weighting for a maximum farfield sidelobe level of -25 dB. Dedopplerisation is implemented too, allowing source tracking during motion and a more accurate noise source level estimation. The cross-array processing consists finally in cross-correlating the time signals provided by the respective line arrays, leading thus to a 2D-directivity pattern with a side-lobe level lower than -10 dB over the whole frequency range. The spatial resolution depends on frequency.

[1] Vertical directivity was also investigated but will be reported elsewhere.

4 Noise emission at constant speed

Constant speed pass-bys ranged from about 20 to 86 km/h for the reference ICE truck and the truck in hybrid mode, and from 19 to 56 km/h for the electric mode. At most speeds, pass-bys were carried out at two different gear ratios: the adapted gear (most appropriate for the test speed) and the inferior gear (one gear lower than the adapted one, inducing a higher engine speed). Engine speed, gear ratio and vehicle speed were available for every pass-by.

4.1 Maximum noise level at 7.5 metres

Using the measured L_{Amax} values as a function of the engine speed and the vehicle speed, for one truck configuration, the noise emission law is determined by fitting the following model to the data, in the least square sense [4]:

$$L_{Amax} = L_{mot}(r) \oplus L_{roll}(v) \quad (1)$$

where $\oplus$ stands for the energetic summation. $L_{mot}(r)$ is the powertrain noise component depending on the engine speed r, and $L_{roll}(v)$ is the rolling noise component depending on the vehicle speed v :

$$L_{mot}(r) = \alpha_{mot} \log\left(\frac{r}{r_{ref}}\right) + L_{0,mot} \quad (2)$$

$$L_{roll}(v) = \alpha_{roll} \log\left(\frac{v}{v_{ref}}\right) + L_{0,roll} \quad (3)$$

where r_{ref} and v_{ref} are respectively the engine (or motor) speed and vehicle speed references.

Figure 4 shows the measures together with the global noise emission laws defined in equations (1), (2) and (3), corresponding to the three truck configurations when driving with the adapted or the inferior gear. Figure 5 compares the noise emission laws for the adapted gear. It may be noticed that the adapted gear shifting strategy differs for the ICE truck and the hybrid truck since their gearboxes are different.

The hybrid truck in hybrid mode is slightly quieter than the reference ICE truck for every speed, whereas the improvement is unquestionable with the electric mode at low speed where it may exceed 8 dB(A) at 20 km/h (Table 1). However this gain reduces at higher speed and becomes insignificant over 50 km/h, due to rolling noise predominance as the noise source analysis will prove it.

Table 1: Global noise reduction of the hybrid truck compared with the conventional ICE truck, at constant speed and adapted gear

	20 km/h	30 km/h	50 km/h
hybrid / ICE	-1.0 dB(A)	-2.7 dB(A)	-1.2 dB(A)
electric/ ICE	-8.4 dB(A)	-6.0 dB(A)	-1.6 dB(A)

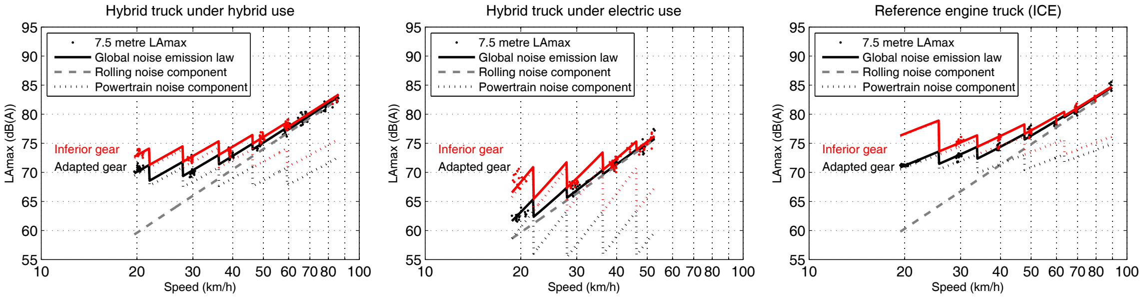

Figure 4: Maximum noise pressure level at constant speed for the hybrid mode (left), the electric mode (middle) and the reference ICE truck (right); • measures at the adapted gear; • measures at the inferior gear; thick lines : global emission law

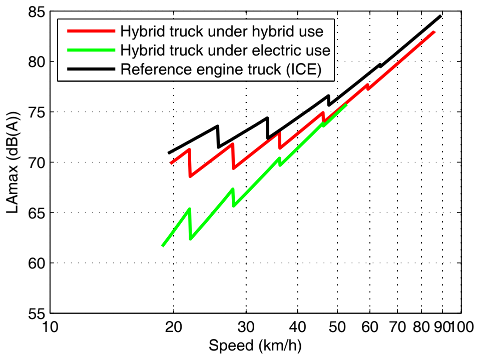

Figure 5: Global noise emission law at constant speed and adapted gear for the hybrid mode (red), the electric mode (green) and the reference ICE truck (black)

4.2 Main noise sources

Investigations using the microphone array allow to draw acoustic pictures of the passing-by vehicle in third-octave bands, pointing out the location and strength of the main noise sources within the limits of the spatial array properties.

The noise sources of the ICE truck and the hybrid truck in hybrid mode are not fundamentally different, even if they may be distinguished by their strength behaviour. However, the noise source distribution in electric mode may differ greatly. At 20 km/h, the main noise sources of the engine truck are located on the front part of the vehicle and are due primarily to the powertrain contribution, whereas the front source for the electric mode, coinciding with the motor position, remains lower than the drive wheel / road contact source (Fig. 6). At higher speeds, rolling noise comes to prominence,with a higher contribution of the drive wheel. From 50 km/h the noise sources are globally identical on every truck (Fig. 7), they only differ in frequency owing to distinct tyre characteristics, particularly the tread design.

Evaluation of the noise sources contribution

Because of the array pattern associated with beamforming, a direct quantitative reading of the noise source contributions on the previous acoustic pictures would lead to overestimated results, in particular at low frequency. A deconvolution approach has been implemented to estimate the source strengths, by minimizing the square error between the measured map and a calculated map resulting from five monopole sources on the vehicle. The position of the sources were constrained within disjoint restricted areas corresponding to the location of the main sources, in accordance with the measurement results. The procedure was validated by comparing

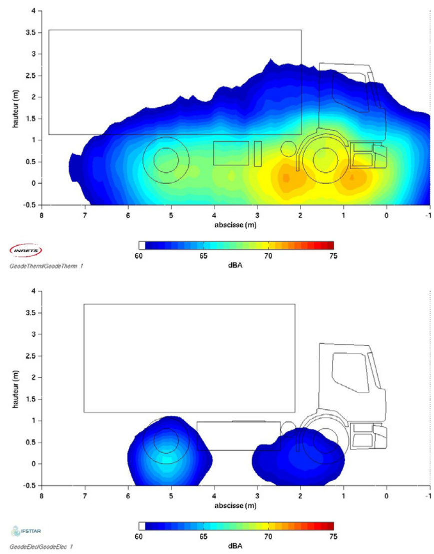

Figure 6: Acoustic map of the ICE truck (top) and the hybrid truck in electric mode (bottom) at 20 km/h – global noise pressure levels on the array

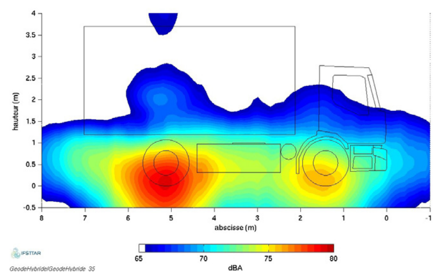

Figure 7: Acoustic map of the hybrid truck in hybrid mode at 50 km/h – global noise pressure levels on the array

the third-octave and global time signatures measured at 7.5 m and the time signatures calculated from a passing-by vehicle model composed of the five monopoles. Since the 2D-array leads to insufficient validation rate, probably due to correlation loss between both line arrays in some cases, it was preferred to use only the horizontal array to assess the power of five uncorrelated point noise sources located on the ground from head to rear of the trucks: in front, near the contact area and behind the steer wheel, between both wheel axles, and near the drive wheel contact area. In the development presented below, the three front sources have been merged in a unique *front source area* covering the cab up to the exhaust system.

Noise source emission laws

The behaviour regarding the parameters is specific to each source type, and noise emission laws have been adapted to each case. The *front source area* includes the powertrain and the steer wheel: its emission law is determined by fitting to the front source levels a model similar to eq.(1), with a powertrain noise component and a rolling noise component. The *drive wheel source* is characterized by the presence of tones, shifting with vehicle speed, in particular due to the tread design periodicity: the emission law in each third-octave is approximated by a broken line. Finally, the *inter-axle source* law depends only on the engine (resp. motor) speed. For space reasons, only the global levels resulting from the summation of the third-octave laws (63 Hz to 4000 Hz) are shown in this paper (Fig. 8), and some comments on frequency behaviour are reported below.

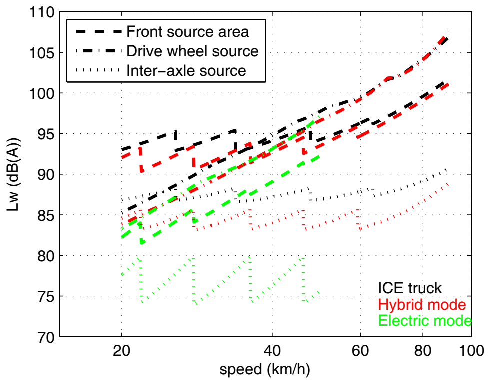

Figure 8: Global noise emission laws of the three main noise source areas for the three truck configurations at constant speed (adapted gear) – acoustic noise power level in dB(A)

Front source area The truck in electric mode is quieter at most frequencies, but the difference is lower or even insignificant at 500 and 630 Hz. In the electric mode, the rolling noise associated with the steer wheel influences the source emission even at low speed, whereas for the ICE and the hybrid mode it plays part only over 60 km/h due to high powertrain noise. The predominance of ICE truck on the truck in hybrid mode results mainly from the high frequencies.

Drive wheel source The ICE truck drive wheel is globally noisier because of the higher contribution of the spectral components linked to the periodical tread design, at low and medium speed. At high speed, global levels for the two trucks are similar, although they contribute higher in distinct frequency bands.

Inter-axle source This source provides a low if not unsignificant contribution to the whole noise emission. Frequency differences occur between trucks but are not detailed thoroughly because of possible contamination of the more powerful neighbouring sources in the processing.

5 Noise emission with accelerating trucks

The truck was either stopped or arriving at constant speed (from 10 to 40 km/h) with the adapted gear, and began to accelerate strongly 10 metres before the first microphone. Both driving directions were investigated. The acceleration rate is higher for the lower initial speeds. The results presented here do not include noise levels with gear shifting during the snapshot at the measurement point. The engine (resp. motor) speed is unavailable for the pass-bys with acceleration.

5.1 Maximum noise level at 7.5m

Instantaneous speeds ranged from 13 to 53 km/h at the most. Maximum noise levels show rather high scattering at a given speed (around 4 dB(A)), unlinked with the truck side measured, for the three truck configurations.

In the absence of engine speed knowledge, the emission law fitted to the measured data is a quadratic or linear polynomial, either in each third-octave band or on the global noise levels. Only the global results are reported here.

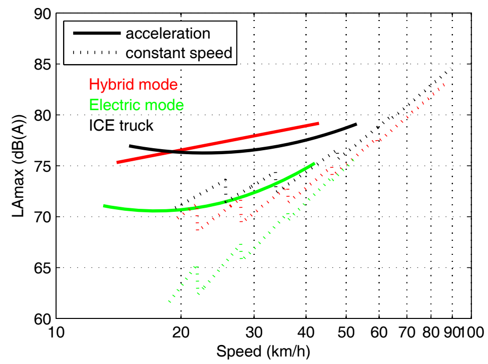

Figure 9: Global noise emission law at 7.5 m with acceleration (full line) and at constant speed / adapted gear (dotted line) for the hybrid mode (red), the electric mode (green) and the reference ICE truck (black) – maximum A-weighted noise pressure levels

Acceleration implies high noise level increase for the three truck configurations (Fig. 9), the maximum pass-by values exceeding even the respective levels at constant speed with inferior gear. The lower the speed (the higher the acceleration), the larger the increase. The hybrid truck in hybrid mode is the noisiest over the most speed range tested. The electric mode remains the quietest: accelerating with the electric mode reduces the noise level emitted up to 6.3 dB(A) in the speed range tested, compared with the accelerating ICE truck.

5.2 Noise source analysis

Vehicle acoustic emission maps indicate a main increase of powertrain noise (including exhaust on the left side for the ICE truck) for both truck configurations with engine, and a noise emission growth associated with the drive wheel area for the electric mode (Fig. 10, to compare with Fig. 6 paying attention to colour scale which could be modified).

The number of available pass-bys from the array measurement is not very high. Thus results concerning the noise source emission laws should be considered as behaviour trends rather than accurate quantitative values. Since engine or motor speed are unknown, the law of the front source area is stated as depending only on speed: $L_{FS}(v) = \alpha_{FS}\log\left(\frac{v}{v_{ref}}\right) + L_{0,FS}$ and the inter-axle source component as constant. Drive wheel law is kept unchanged but the limited speed range reduces the result precision.

Figure 11, as compared with figure 8, highlights the noise emission increase of the front source area, a priori ascribable to the powertrain, for the two truck configurations with engine, while there is no significant increase with the electric

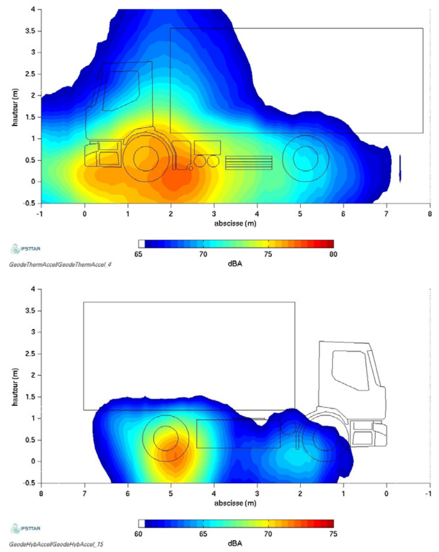

Figure 10: Acoustic map of the ICE truck (top) and the hybrid truck in electric mode (bottom) with acceleration at 20 km/h – global noise pressure levels on the array

mode. The ICE truck is the only truck to point out side differences for this source. Regarding the drive wheel source, the emitted noise increases in any case, probably due to higher traction stress, with emphasis on the narrowband spectrum components. Rolling noise generated by the drive wheel is then the prevalent source of the accelerating truck in electric mode. Finally, the acceleration effect is still noticeable at 50 km/h.

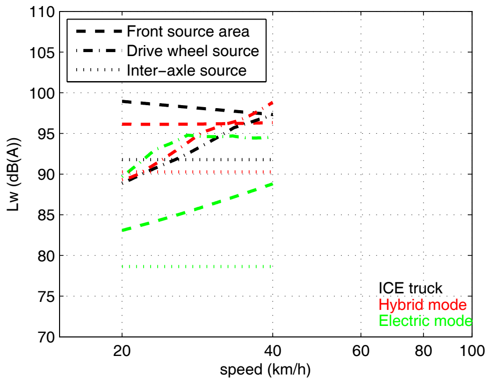

Figure 11: Global noise emission laws of the three main noise source areas for the three truck configurations with acceleration – acoustic noise power in dB(A)

6 Noise emission with braking

The truck arrived at constant speed (20 or 40 km/h) with the adapted or the inferior gear, and began to brake 10 metres before the first microphone, either using the service brake or the exhaust brake or both of them. The exhaust brake mode is unavailable in electric mode. Both sides were investigated. The engine or motor speed is not available.

Neither the braking type (when available) nor the truck side affects significantly the maximum noise pressure levels at 7.5 m whatever the truck configuration. Noise levels are higher than at constant speed (adapted gear), except for the ICE truck at low speed (Fig. 12). The braking hybrid truck in hybrid mode is slightly noisier than the braking ICE truck, but the electric mode may reduce braking noise emission up to 3.2 dB(A).

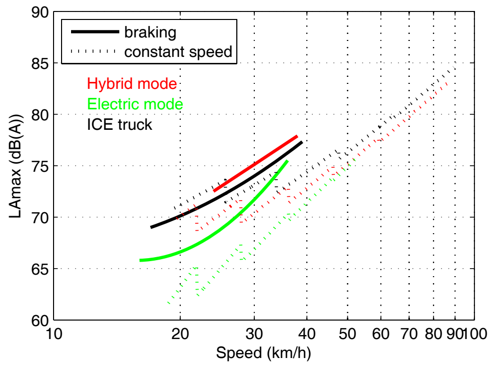

Figure 12: Global noise emission law at 7.5 m with braking (full line) and at constant speed / adapted gear (dotted line) for the hybrid mode (red), the electric mode (green) and the reference ICE truck (black) – maximum A-weighted noise pressure levels

7 Conclusion

This research proved that, at urban speed, the GEODE hybrid truck is slightly quieter than a conventional ICE truck, mainly due to lower powertrain noise component. However, it becomes noisier when accelerating, partially owing to rolling noise increase from the drive wheel area. On the other hand, a dramatic noise reduction occurs when driving in electric mode: it may exceed 8 dB(A) at constant low speed, but reduces at higher speeds and vanishes at 50 km/h. This mode still remains attractive in acceleration or braking situations, although the improvement is lower when compared with a conventional ICE truck. In the electric mode, noise is dominated by the drive wheel rolling noise, which would be the next stake if further noise reduction is expected.

Acknowledgments

This work was supported by the Rhone-Alpes Region. The authors thank project leader Renault Trucks.

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