



**HAL**  
open science

## **Sensitivity analysis and propagation of uncertainty for the simulation of vehicle pass-by noise**

Hichem Hamdad, Charles Pezerat, Benoit Gauvreau, Christophe Locqueteau,  
Yannick Denoual

### ► **To cite this version:**

Hichem Hamdad, Charles Pezerat, Benoit Gauvreau, Christophe Locqueteau, Yannick Denoual. Sensitivity analysis and propagation of uncertainty for the simulation of vehicle pass-by noise. *Applied Acoustics*, 2019, 149, pp85-98. <10.1016/j.apacoust.2019.01.026>. <hal-02406822>

**HAL Id: hal-02406822**

**<https://hal.science/hal-02406822v1>**

Submitted on 27 May 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

## Sensitivity analysis and propagation of uncertainty for the simulation of vehicle pass-by noise

Hichem Hamdad, Benoit Gauvreau, Charles Pezerat, Christophe Locqueteau,  
Yannick Denoual

► **To cite this version:**

Hichem Hamdad, Benoit Gauvreau, Charles Pezerat, Christophe Locqueteau, Yannick Denoual. Sensitivity analysis and propagation of uncertainty for the simulation of vehicle pass-by noise. Applied Acoustics, Elsevier, 2019, 149, pp85-98. 10.1016/j.apacoust.2019.01.026 . hal-02406822

**HAL Id: hal-02406822**

**<https://hal.archives-ouvertes.fr/hal-02406822>**

Submitted on 27 May 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Sensitivity analysis and propagation of uncertainty for the simulation of vehicle pass-by noise

Hichem HAMDAD<sup>a,b,c,\*</sup>, Charles PÉZERAT<sup>b</sup>, Benoît GAUVREAU<sup>c</sup>, Christophe LOCQUETEAU<sup>a</sup>, Yannick DENOUAL<sup>a</sup>

<sup>a</sup>Renault, CTA G19 0 10, Le Parc de Gaillon, 27940 Aubevoye, France

<sup>b</sup>Laboratoire d'Acoustique de l'Université du Mans, LAUM - UMR 6613 CNRS, Le Mans Université, Avenue Olivier Messiaen, 72085 LE MANS CEDEX 9, France

<sup>c</sup>Ifstar, Cerema, UMRAE, Route de Bouaye, 44344 Bouguenais, France

---

## Abstract

The study presented in this paper aims at developing an aid to the modeling of the pass-by noise of a vehicle, as called for in regulatory testing. The goal is to accurately predict and evaluate noise emissions earlier in the vehicle development cycle, *i.e.* before the industrialization stage. For these reasons, a synthesis model is developed. This model combines the acoustic flow of the most influent sources (powertrain, intake, exhaust tail, exhaust line, tire/road noise), with the acoustic transfer between these sources and the microphone located at 7.5 m from the axis of the test track, taking into consideration the motion of the vehicle. The input parameters of these models are considered uncertain; therefore, an uncertainty quantification study is first performed. These uncertainties are then propagated in these models using quasi-Monte Carlo methods. Finally, a sensitivity analysis study is carried out to study the impact of the variability of the input parameters on the variability of the output noise levels of the synthesis models. Influential parameters have been identified and classified by vehicle family.

**Keywords:** Vehicle pass-by noise, quantification of uncertainty, propagation of uncertainty, global sensitivity analysis.

---

## 1. Introduction

European legislation requires car manufacturers to ensure that the noise levels of their vehicles do not exceed a certain limit. The Economic Commission for Europe Regulation, ECE R51.03 [1], specifies the permissible levels that a motor vehicle can emit while driving. This regulation is applied since July 1st, 2016 to replace the former ECE R51.02 regulation [2], with a new test method and a tightening of the permissible levels. This will be done in three stages, from 74 dB (A) under the former ECE R51.02 regulation [2] to 68 dB (A) in 2024. This noise level is equivalent to that emitted by today's electric cars. Joint measurements under the two regulations, ECE R51.02 [2] and ECE R51.03 [1], carried out in an official framework in 2012, showed that 97% of French vehicles did not comply with the 68 dB (A) of the new regulation [3, 4]. This will be a major challenge for automotive manufacturers and suppliers. Indeed, at the end of the project, it is no longer possible to change the design if a vehicle exceeds the permissible limit. At this stage of the project, only palliative solutions can be proposed. These solutions are expensive and can deteriorate the vehicle performance. In addition, competitive pressure is imposing shorter development times and lower costs on manufacturers. To maintain its competitiveness, Renault company has therefore modified its research and development processes, in particular by increasing the number and quality of numerical simulations and by reducing the number and duration of validation tests. However, the accuracy of the models available in the company is

still insufficient, today, to predict the noise of a vehicle under development.

The objective of this paper is to develop an aid to the whole modelling of the pass-by noise of a vehicle in accordance with the regulatory test requirements of the new standard. The goal is to predict and evaluate accurately the noise emissions earlier in the vehicle development cycle. For these reasons, a synthesis model is developed to predict the pass-by noise of a vehicle. The latter combines the different "links", *i.e.* the acoustic characteristics of the different subsystems of the vehicle that contribute to the external noise level. The various elements of this vibro-acoustic chain are divided into *sources* (powertrain, intake, exhaust tail, exhaust line, tire/road noise) and *transfers*, which represent insulation and/or propagation (powertrain compartment walls, openings, absorbent materials, insulation screens).

In the next section, the procedure for measuring the level of vehicle pass-by noise under the new regulation is presented. Section 3 is devoted to the presentation of the synthesis model developed and its operating principle. The input parameters of this model are then considered uncertain, that is why the proposed approach aims to identify their uncertainty and variability to understand how they propagate. A global sensitivity analysis study is then carried out to study the impact of the uncertainty and variability of the input parameters on the outputs of the model. The main steps of this study are presented in Section 4. Finally, the main results are presented and discussed in Section 5.

---

\*. Corresponding author.

Email address: [hichem.hamdad@gmail.com](mailto:hichem.hamdad@gmail.com) (Hichem HAMDAD)

## 2. Measurement procedure

The regulation of the Economic Commission for Europe, ECE R51.03 [1] refers to the new international standard ISO 362: 2015 [5], which describes the new procedure for measuring the vehicle pass-by noise. This test procedure is used to evaluate the representative noise emission of a vehicle under conditions typical of urban traffic. Indeed, this new method consists in combining the maximum level of external noise of a vehicle during acceleration and at a constant speed of 50 km/h.

The method for measuring the pass-by noise of vehicles of category M1<sup>1</sup>, according to ISO 362: 2015 [5], is detailed here. As with the previous ISO 362: 1998 standard [6], the test is performed on a track that complies with the requirements of ISO 10844 [7] (tracks designed to be particularly quiet have a lower sound emission than tracks ISO 10844 [7]). The estimate of pass-by noise level  $L_{urban}$  (expressed in dB (A)), representative of the external noise level of a vehicle under conditions typical of urban traffic, is done under partial load, *i.e.* based on measurements under full load acceleration and at a constant speed of 50 km/h. For the full load acceleration test, the driver must accelerate so that the vehicle speed is at 50 km/h in the middle of the test track PP' (see Figure 1a). The noise levels recorded at both microphones are A-weighted and then converted to an overall value. The values used correspond to the maximum value during the vehicle passage on the track. Four tests are performed consecutively, all within a variation range of 2 dB (A). The noise levels corresponding to the four runs are then averaged at each microphone, for both full load acceleration and constant speed of 50 km/h. The largest values recorded on each side are used to calculate the partial load noise level  $L_{urban}$ .

Based on measurements and statistical analyses of urban traffic noise [1], a formula has been developed to calculate the pass-by noise level  $L_{urban}$ . This formula depends on the two noise levels corresponding to the passage under full load acceleration and at a constant speed of 50 km/h, as well as power-to-mass ratio of the vehicle:  $PMR$  (in kW/t)<sup>2</sup>. The  $PMR$  ratio allows to calculate two accelerations for each vehicle:

- The target acceleration  $a_{urban}$  (in  $m/s^2$ ) is defined as the typical acceleration in an urban environment. The latter is obtained from statistical study. Its expression depends on the  $PMR$  and corresponds to [1]:

$$a_{urban} = 0.63 \log PMR - 0.09 \quad (1)$$

- The reference acceleration for the wide-open-throttle test  $a_{wot ref}$  (in  $m/s^2$ ) is defined as the acceleration required during the full load acceleration test. It is expressed in terms of the  $PMR$  of the vehicle [1]:

$$a_{wot ref} = 1.59 \log PMR - 1.41 \quad \text{if } PMR \geq 25 \quad (2)$$

1. Category M1: vehicles used for the carriage of passengers with not more than eight seats in addition to the driver's seat.

2.  $PMR$ : Power to Mass Ratio index. It is defined by:  $PMR = \frac{P_n}{m_{ro}} \times 1000$  where  $P_n$  is the power of the vehicle (in kW).  $m_{ro}$  (Mass of vehicle in running order) is the mass of the vehicle (in kg). It represents the mass of the vehicle with its fuel tank filled to at least 90% of its capacity, as well as the driver's mass set at 75kg.

or

$$a_{wot ref} = 0.63 \log PMR - 0.09 \quad \text{if } PMR < 25 \quad (3)$$

### 2.1. In the case of a single gear ratio

If a specific gear ratio (n) gives an acceleration within a tolerance interval of  $\pm 5\%$  of the reference acceleration for the wide-open-throttle test  $a_{wot ref}$ , and not exceeding  $2 m/s^2$ , then this gear ratio will be chosen to perform the test. The pass-by noise level  $L_{urban}$  is calculated by performing a linear interpolation between the two recorded sound levels (see Figure 1b):

$$L_{urban} = L_{wot(n)} - K_p(L_{wot(n)} - L_{crs(n)}) \quad (4)$$

where  $L_{wot(n)}$  and  $L_{crs(n)}$  (expressed in dB (A)) represent respectively the sound pressure levels corresponding to the full load acceleration of the vehicle  $a_{wot(n)}$  (in  $m/s^2$ ) and at a constant speed of 50 km/h for the gear ratio (n). The partial power factor  $K_p$ , represents a dimensionless numerical quantity. It is used to interpolate the test results under full load acceleration and at constant vehicle speed. This factor is given by the following equation [1]:

$$K_p = 1 - \frac{a_{urban}}{a_{wot(n)}} \quad (5)$$

### 2.2. In the case of two gear ratios

In most cases, there is no gear ratio to approach the reference acceleration for the wide-open-throttle test  $a_{wot ref}$ . In this case, the acceleration  $a_{wot ref}$  is framed by the nearest accelerations of the two gear ratios:  $a_{wot(n)}$  and  $a_{wot(n+1)}$ <sup>3</sup> (see Figure 2). The pass-by noise level  $L_{urban}$  is calculated as follows [1]:

$$L_{urban} = L_{wot rep} - K_p(L_{wot rep} - L_{crs rep}) \quad (6)$$

where  $L_{wot rep}$  and  $L_{crs rep}$  (in dB (A)) correspond respectively to the linear interpolation between the two sound pressure levels of the gear ratio (n) and (n+1), under full load acceleration  $a_{wot ref}$  and at a constant speed of 50 km/h. They are given by the following equations [1]:

$$L_{wot rep} = L_{wot(n+1)} + K(L_{wot(n)} - L_{wot(n+1)}) \quad (7)$$

$$L_{crs rep} = L_{crs(n+1)} + K(L_{crs(n)} - L_{crs(n+1)}) \quad (8)$$

where  $L_{wot(n)}$  and  $L_{wot(n+1)}$  (in dB (A)) represent the sound pressure levels corresponding to the accelerations  $a_{wot(n)}$  and  $a_{wot(n+1)}$  respectively, and where  $L_{crs(n)}$  and  $L_{crs(n+1)}$  (in dB (A)) represent the sound pressure levels corresponding to constant speed runs for the gear ratios (n) and (n+1) respectively.  $K$  is the gear ratio weighting factor. It is used to linearly interpolate the noise levels of the two gear ratios, as shown in Figure 2. The  $K$  factor is given by the following relationship [1]:

$$K = \frac{a_{wot ref} - a_{wot(n+1)}}{a_{wot(n)} - a_{wot(n+1)}} \quad (9)$$

3. If the acceleration value of the gear ratio (n) exceeds  $2 m/s^2$ , the gear ratio (n+1) will be used for the test. However, if the acceleration of the gear ratio (n+1) is less than the target acceleration  $a_{urban}$ , in this case both gear ratios (n) and (n+1) are used.

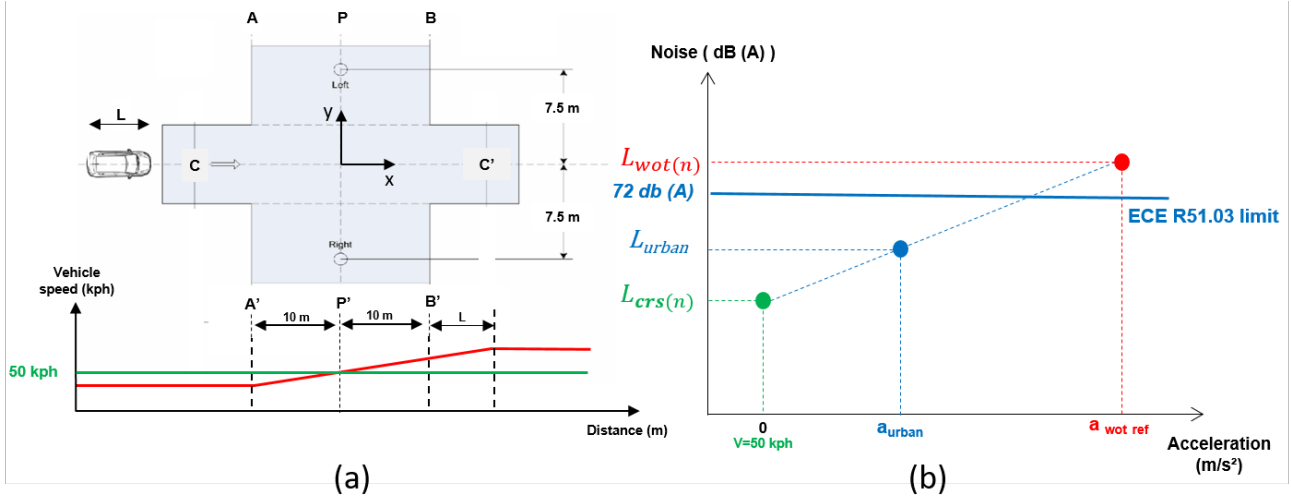


FIGURE 1: Estimated noise level  $L_{urban}$  according to the new ECE R51.03 regulation

In the case of two gear ratios, the partial power factor  $K_p$  is given by the following equation [1]:

$$K_p = 1 - \frac{a_{urban}}{a_{wot\ ref}} \quad (10)$$

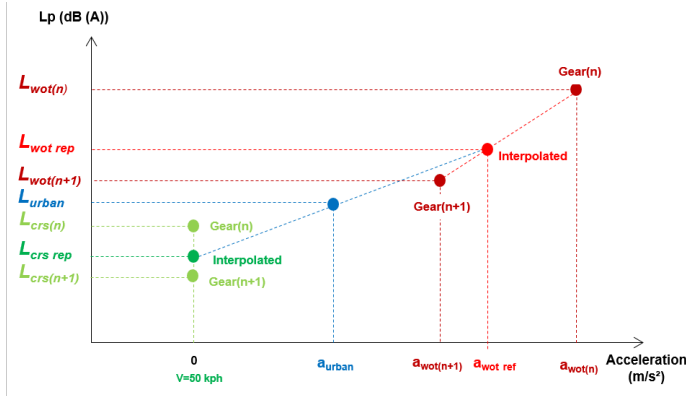


FIGURE 2: Estimated noise level  $L_{urban}$  in the case of two gear ratios according to ECE R51.03 regulation

### 3. Pass-by noise prediction model

Prediction model, or synthesis model, is based on a simple Source-Transfer-Receiver model [8, 9, 10, 11, 12], also known as the TPA (Transfer Path Analysis) method. The method is based on the principle that, for a source divided into  $k$  sources assumed to be uncorrelated, it can be written that the contribution of each source is the product of the acoustic flow multiplied by the acoustic transfer between this source and the microphone which is 7.5 m from the track axis. Nevertheless, the assumption of uncorrelated sources generates limitations of the method in low frequency (up to about 300 Hz). This method is used not only to reproduce the level of vehicle pass-by noise, but also to

classify sources and analyze their contribution to total noise separately. It is thus possible to define a noise level target for each source, by acting on the source modifying the structure, or by acting on the acoustic transfer adding absorbent or insulating treatments. The noise emitted by each source is thus calculated at discrete positions (receiver point  $j$ ) over the entire length of the test track as follows:

$$P_j^2(\omega) = \sum_{i=1}^k \dot{Q}_i^2(\omega) \cdot TF_{ij}^2(\omega) \quad (11)$$

where  $\dot{Q}_i = \omega \cdot Q_i$  is the volume acceleration flow rate corresponding to the source  $i$  (expressed in  $m^3/s^2$ ) and  $\omega$  (in rad/s) is the angular velocity.  $k$  corresponds to the number of sources.  $P_j$  (in Pa) is the sound pressure at the measurement point  $j$ , and finally  $TF_{ij}$  (expressed in  $Pa \cdot m^{-3} \cdot s^2$ ) represents the transfer function between the source  $i$  and the measurement point  $j$ .

However, the noise level of tire/road contact is characterised in a different way. Indeed, the sound contribution of tire/road contact is directly measured at 7.5 m, and this for several vehicle speeds (from 30 to 80 km/h). A logarithmic regression is then performed to obtain the coefficients  $A_p$  and  $B_p$  which depend on the tire, as illustrated in the following empirical equation [13]:

$$L_{pc} = A_p \log\left(\frac{V}{50}\right) + B_p \quad (12)$$

where  $L_{pc}$  (in dB(A)) represents the overall noise level of the tire.  $A_p$  and  $B_p$  are constants that depend on the tire and the vehicle's position on the track, and  $V$  represents the vehicle speed in km/h.

#### 3.1. Operating principle

The acoustic radiation of the sources as well as the transfer functions are constantly changing during the test. Indeed, the contribution of each noise sources varies according to the conditions under which the vehicle passes through the test track.

The acoustic radiation of the sources depends mainly on the engine speed, while the acoustic transfers depend on the position of the vehicle on the track. This must be taken into account in the model for predicting the level of pass-by noise. To do this, it is necessary to use the same run conditions as the regulatory tests and to calculate the vehicle accelerations for each gear ratio during runs under full load acceleration (the vehicle acceleration is considered constant). It also allows us to choose the acceleration of the gear ratio which approaches  $a_{wot\ ref}$  to  $\pm 5\%$ . In the case where no gear ratio allows to approach this reference acceleration, the two gear ratios (n) and (n+1) are chosen, which allow to frame  $a_{wot\ ref}$  (see Figure 2). Figure 3 represents a complete diagram of the operating principle of the synthesis model.

The acceleration  $a_{wot(n)}$  that interests us is the one that corresponds to a speed of  $V = 50\text{ km/h}$ . In order to calculate this acceleration, we use the fundamental principle of dynamics, as illustrated in the Eq. (13), with  $R$  (in  $m$ ) the radius of the tire,  $I_n$  (expressed in  $kg.m^2$ ) represents the moment of inertia of the vehicle's kinematic chain,  $Fr$  (in  $N$ ) designates the resistive force at  $50\text{ km/h}$ ,  $Fd_{(n)}$  (in  $N$ ) corresponds to the driving force developed by the vehicle at  $50\text{ km/h}$  for the gear ratio (n), and finally  $m_g$  (in  $kg$ ) represents the total mass<sup>4</sup>.

$$a_{wot(n)} = \frac{Fd_{(n)} - Fr}{m_g + \frac{I_n}{R^2}} \quad (13)$$

The resistive force  $Fr$  depends on the aerodynamic force  $F_{aero}$  (in  $N$ ) which is proportional to the square of the vehicle speed (the speed here is set at  $50\text{ km/h}$ ), on the rolling resistance force  $R_r$  (in  $N/t$ ), on the force related to bearing friction  $F_{bearing}$  (in  $N$ ) and brake friction  $F_{brake}$  (in  $N$ ). The resistive force is given by:

$$Fr = F_{aero} + F_{bearing} + F_{brake} + R_r \frac{m_g}{1000} \quad (14)$$

The driving force  $Fd_{(n)}$  that the vehicle develops is expressed as a function of the engine torque  $\tau$  (in  $Nm$ ). It is given by the Eq. (15).  $T_y$  is the transmission efficiency in percentage (%), and  $\omega_e$  is the engine rotation speed in  $rad/s$ , with  $\omega_e = \frac{2\pi N_e}{60}$ .

$$Fd_{(n)} = \frac{3600 \omega_e}{1000 V} \cdot \frac{T_y}{100} \cdot \tau = \frac{120 \pi}{V_{mille(n)}} \cdot \frac{T_y}{100} \cdot \tau \quad (15)$$

with  $V_{mille(n)}$  (expressed in  $km/h$ ) represents the vehicle speed when the engine speed  $N_e = 1000\text{ rpm}$ . This parameter depends on the gearbox ratio and the circumference of the tire. The parameter  $V_{mille(n)}$  allows us to make the link between the vehicle speed  $V$  and the engine speed  $N_e$  (expressed in  $rpm$ ), using the following linear relationship:

$$V = \frac{V_{mille(n)}}{1000} N_e \quad (16)$$

4. The total mass  $m_g$ , corresponds to the mass of the vehicle  $m$  with its fuel tank filled to at least 90% of its capacity, as well as the mass of the driver  $m_d$ . The mass  $m_g$  is different from the mass  $m_{ro}$  (Mass of vehicle in running order). Indeed, the mass  $m_g$  is used to calculate the vehicle's performance (i.e. accelerations). The model user is therefore free to choose the real mass of the driver, unlike the mass  $m_{ro}$  which is used in the regulation to calculate the value  $PMR$ , where the mass of the driver is set at 75 kg.

$\tau$  corresponds to the full load torque. This is the torque developed by the engine when the vehicle's accelerator pedal is fully depressed. This parameter is directly measured as a function of the engine rotation speed.

The accelerations  $a_{wot(n)}$  are then calculated with the Eq. (13). Then we choose the acceleration that approaches  $a_{wot\ ref}$  to  $\pm 5\%$ . In case no gear ratio allows to approach this reference acceleration, it is framed with  $a_{wot(n)}$  and  $a_{wot(n+1)}$  (see Figure 2). From the acceleration  $a_{wot(n)}$  and/or  $a_{wot(n+1)}$ , the vehicle speed is calculated over the entire length of the test track<sup>5</sup>. To do this, we assume that the vehicle is a material point of mass  $m_g$  in translation in a Galilean reference frame between the entrance of track AA' and the complete exit of the vehicle from track BB' (see Figure 1a). The kinetic energy theorem is applied to calculate the speed  $V$  as a function of the vehicle's position on the track  $X_v$ :

$$\frac{1}{2} \cdot \frac{1000}{3600} (V^2 - V_0^2) = a_{wot(n)} (X_v - X_{v0}) \quad (17)$$

with  $V_0 = 50\text{ km/h}$  corresponding to the vehicle speed at the position  $X_{v0} = 0\text{ m}$  (on line PP', see Figure 1a).

The vehicle speed  $V$  allows to obtain the contribution of the tire/road contact by using the Eq. (12). For full load acceleration configurations, a measured value related to the effect of wheel torque  $\tau_{tire}$  (in  $Nm$ ) is added to the contribution of the tire/road contact at constant speed.

The engine speed  $N_e$  is obtained from the vehicle speed, using the Eq. (16). It gives the possibility to obtain the power of the sources  $Wac_i$  (in Watt) corresponding to the current rotation speed for each position of the vehicle on the track  $X_v$ . These powers will be transformed into a volume acceleration flow rate  $\dot{Q}_i$ , before being multiplied by the appropriate transfer functions  $TF_{ij}$  to obtain the contribution of each source (see Eq. (11)). Thus, at the output of the model, we obtain the noise levels for each run:  $L_{crs(n)}$ ,  $L_{wot(n)}$ ,  $L_{crs(n+1)}$ ,  $L_{wot(n+1)}$ . The noise level  $L_{urban}$  is obtained by interpolating these noise levels.

### 3.2. Overall synthesis model

The question of the powertrain modeling subsists. Indeed, this is a very complex noise source that must be refined. The procedure used in this study for measuring the acoustic flow and the transfer functions related to the powertrain are detailed below.

The powertrain is modeled here by a single point source (see Figure 4). To quantify the volume acceleration flow rate of this source, measurements are made on the powertrain extracted from the vehicle and installed on a test bench. The tests are carried out under the same load conditions as those corresponding to the pass-by noise test. The total acoustic power of the powertrain  $Wac_i$  is obtained by intensity measurements, with the engine running at  $3000\text{ rpm}$ . To obtain the acoustic power as a function of the engine speed  $N_e$ , microphones are placed at a distance of  $1\text{ m}$  in front of each side of the powertrain. Then the total power is extrapolated using the root mean square of

5. For the stabilized speed configuration, the vehicle speed is considered constant  $V = 50\text{ km/h}$  for all vehicle positions  $X_v$ .

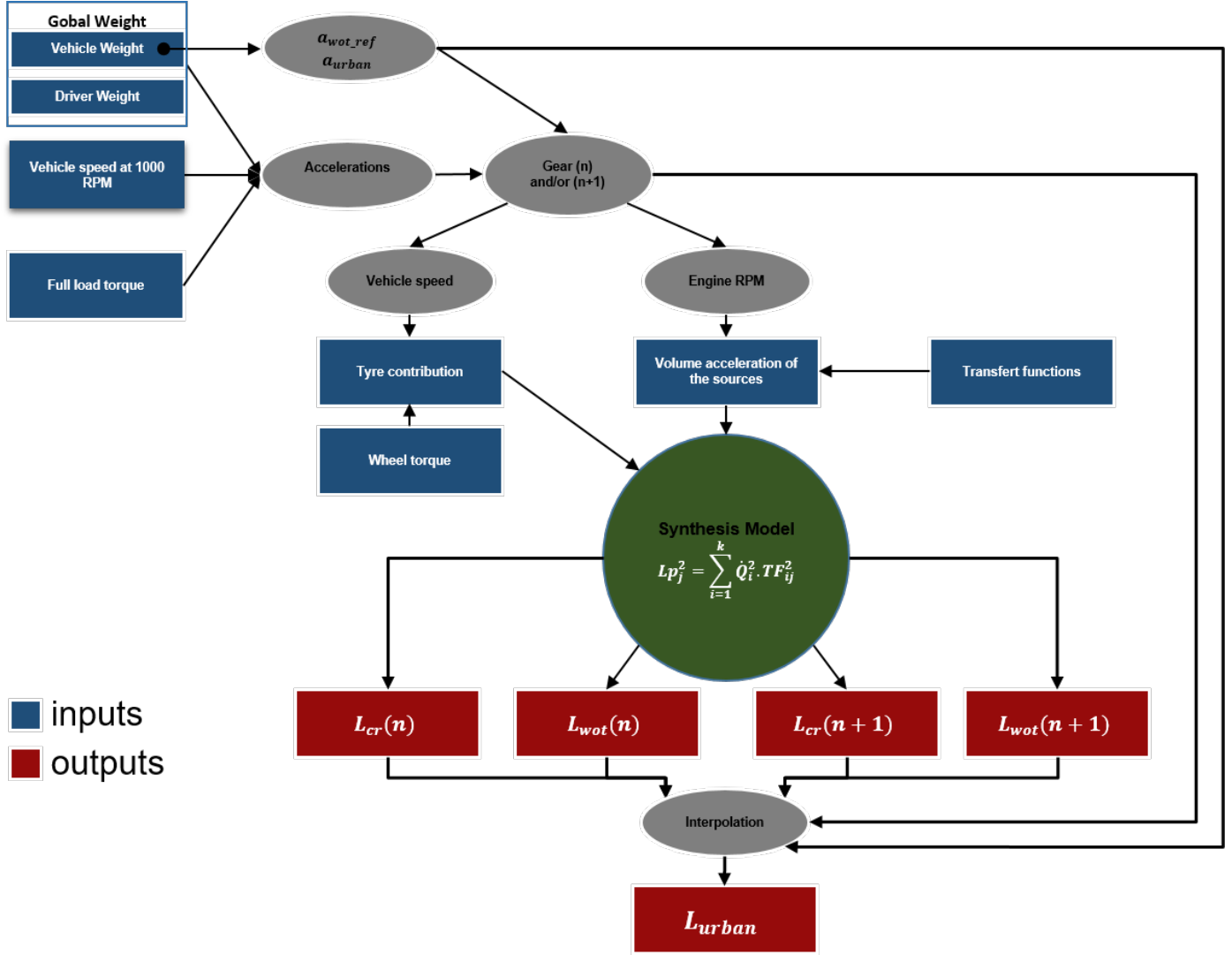


FIGURE 3: Complete diagram of the synthesis model

the pressure levels of all microphones at 1 m. Thus the powertrain is assimilated to a single acoustic monopole  $i$  with a volume acceleration flow rate  $\dot{Q}_i$ , baffled by the powertrain wall. The acoustic volume acceleration flow rate is obtained from the acoustic power of the powertrain  $Wac_i$ :

$$\dot{Q}_i(\omega) = \sqrt{\frac{2\pi c}{\rho} Wac_i(\omega)} \quad (18)$$

where  $c$  represents the velocity of sound (in  $m/s$ ) and  $\rho$  represents the density of air (in  $kg.m^{-3}$ ).

The powertrain is then divided into 21 zones. For each zone, a transfer function  $TF_{ij}$  is measured by the reciprocal method. For this purpose, a calibrated sound source with a known flow rate is moved 1 m between each measurement along a line located 7.5 m from the centre line of the track and 1.2 m high. The 21 measured acoustic transfers are averaged quadratically to represent the powertrain by a point source.

In this study, the acoustic flow rate of the sources and the

transfer functions are represented by overall values. Indeed, the value to be analyzed at the output of the model, *i.e.* the level  $L_{urban}$  mentioned in ECE Regulation R51.03 [1] is given as a A-weighted overall value. We can therefore imagine a model where all the source powers (powertrain, intake, exhaust tail, exhaust line) and their adequate transfer functions would also be reduced to overall values (see Figure 4).

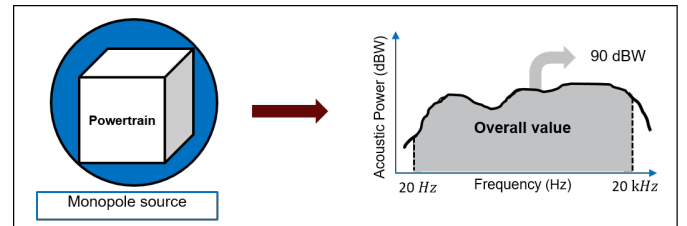


FIGURE 4: overall synthesis model

## 4. Sensitivity analysis and propagation of uncertainty

The application of sensitivity analysis and uncertainty propagation methods to the vehicle pass-by noise prediction model is presented in this section. To perform sensitivity analysis and propagation of uncertainty, it is assumed that the model is sufficiently accurate to predict the behaviour of the system (the equations are relevant and the approximations introduced in the model are controlled), and only the *parametric uncertainties* are focused on. Indeed, calculations are generally made in a deterministic way; however, in reality, the values of the input parameters are not exactly known and are therefore subject to uncertainties. A probabilistic approach is then better adapted by considering the input and output parameters of the model as random variables. The uncertainty of these input parameters is then propagated in the model in order to characterize the variability generated in the variables of interest at the output of the model. Finally, the sensitivity analysis takes place at this stage in order to study the impact of the variability of each input parameter on the output(s) of the model. Figure 5 summarizes in a general framework all the steps for uncertainty studies [14]:

1. specification of the problem: definition of the model(s), input and output variables, quantities of interest as well as the objectives of the study;
2. quantification of uncertainties related to the input parameters of the model, and attribution of probability distributions, based on available or measured data, literature or expert judgment. This is an important and delicate step, which can be very time-consuming;
3. propagation of uncertainties (*forward process*) in the model and evaluation of the variability of the output induced by the uncertainty of the input data;
4. sensitivity analysis is the *backward process*, it allows to measure the sensitivity of the variables of interest to the input parameters;
5. depending on the result obtained, it is sometimes important to redefine the problem and return to the different stages of the study.

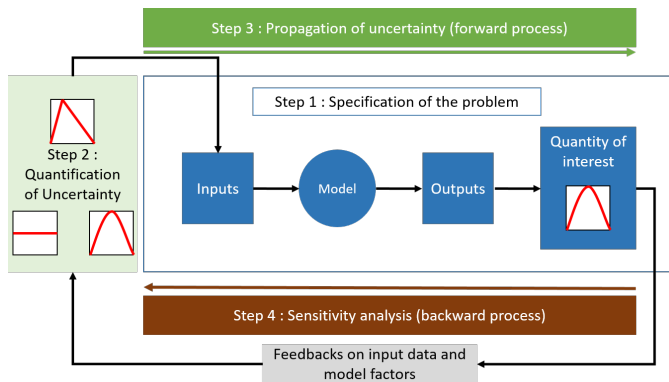


FIGURE 5: The basic steps to perform a sensitivity analysis study

### 4.1. Quantification of uncertainties

It is assumed that the model accurately predict the behaviour of the system if the input parameters are perfectly known; however, the values of the input parameters are not exactly known, and are therefore subject to uncertainty. For this reason, quantifying the sources of uncertainty on input parameters is an important step for uncertainty studies.

In this study, the input parameters of the synthesis model are represented by random variables. Their uncertainties are quantified using mainly expert judgment or the maximum entropy principle [15, 16, 17]. However, some measurements are made on some parameters, where a distinction is made between *measurement uncertainty*, which is related to repeatability, reproducibility and test conditions, and *production variability*, that corresponds to the differences between vehicles of the same technical definition produced with the same industrial tools.

Usually, all input parameters presented in the Section 3 are measured one time for each vehicle type. The aim now is to determine the uncertainty associated to each of these parameters, which corresponds respectively to a fluctuation around this experimental nominal value. We also assume that this uncertainty is the same for all types of vehicles. This approach for dealing with uncertainties allows the treatment of dependencies as a relationship between parameters with a term "noise" added around the nominal value [18]. The probability distributions assigned to the input parameters of the synthesis model are presented in the Table 1. The methods used to characterize the uncertainty of certain parameters and the probability distributions assigned to them are presented below (see Table 1).

#### 4.1.1. Measurement uncertainty

**The total mass  $m_g$ :** to determine the measurement uncertainty related to the vehicle mass  $m$ , we measured that of the same vehicle several times. An uncertainty of  $\pm 0.5$  kg was observed. Concerning the mass of the driver  $m_d$ , its nominal value is set at 75 kg. We considered an uncertainty corresponding to  $\pm 25$  kg. These two parameters are completely independent, and their sum corresponds to the global mass  $m_g$  with  $m_g = m + m_d$ . The main purpose of separating these two parameters is that the vehicle mass is used to calculate the power-to-mass ratio of the vehicle  $PMR$ , and therefore the target accelerations  $a_{urban}$  and  $a_{wot ref}$  (see Eq. (1), (2) and (3)), but also to calculate the vehicle's performance, *i.e.* the vehicle accelerations for each gear ratio using Eq. (13). However, the driver's mass is only used to calculate the vehicle's performance.

**The speed  $V_{mille}$ :** the vehicle speed  $V$  and the engine speed  $N_e$  are measured on several vehicles during the tests. The values of the parameter  $V_{mille}$  are then calculated for each vehicle from the Eq. (16), and compared with the nominal value given by the vehicle's technical definition. We noted that the values obtained are normally distributed around this nominal value. therefore, a normal distribution has been attributed to the uncertainty of this parameter, with a standard deviation  $\sigma = 0.5$  % of the nominal value.

Variable		Measurement uncertainty	Production variability
Total mass $m_g$ (kg)	Vehicle mass $m$ (kg)	U(-0.5,0.5)	U(-2,2)
	Driver's mass $m_d$ (kg)	U(-25,25)	/
$V_{mille}$ (%)		$\mathcal{N}(0,0.5^2)$	U(-2.8,2.8)
Engine torque $\tau$ (%)		U(-5,5)	U(-5,5)
$Wac_{cr}$ (dBW)	Powertrain	U(-2,2)	U(-0.5,0.5)
	Exhaust tail	U(-2,2)	U(-0.5,0.5)
	Exhaust line	U(-2,2)	U(-0.5,0.5)
	Intake tail	U(-2,2)	U(-0.5,0.5)
$Wac_{wor}$ (dBW)	Powertrain	U(-1,1)	U(-0.5,0.5)
	Exhaust tail	U(-1,1)	U(-0.5,0.5)
	Exhaust line	U(-1,1)	U(-0.5,0.5)
	Intake tail	U(-1,1)	U(-0.5,0.5)
$TF$ (dB (A))	Powertrain	U(-1,1)	U(-0.5,0.5)
	Exhaust tail	U(-1,1)	U(-0.5,0.5)
	Exhaust line	U(-1,1)	U(-0.5,0.5)
	Intake tail	U(-1,1)	U(-0.5,0.5)
$L_{pc}$ (dB (A))	At constant speed	$\mathcal{N}(0,0.6^2)$	U(-0.5,0.5)
	Wheel torque $\tau_{tire}$	U(1,2.5)	U(-0.5,0.5)

TABLE 1: Probability distributions assigned to the input parameters of the synthesis model<sup>6</sup>

**Engine torque  $\tau$ :** Since there are not sufficient measures to characterize the uncertainty associated with the engine torque  $\tau$ , we used expert judgment to assign a uniform probability distribution corresponding to  $\pm 5\%$  of its nominal value.

**Acoustic power of the sources  $Wac$ :** we also used expert judgment to characterize the uncertainty associated with the acoustic power of the sources. A uniform distribution corresponding to  $\pm 1$  dB (A) is then attributed to the power of the sources under full load conditions  $Wac_{wor}$ . However, for constant speed conditions, the method of measuring the acoustic power of the sources  $Wac_{cr}$  is very uncertain. Indeed, the load conditions corresponding to the constant speed run are difficult to reproduce on the bench. That is why we have attributed to the uncertainty of these powers a uniform distribution of  $\pm 2$  dB (A).

**Transfer functions  $TF$ :** several transfer functions are measured in repeatability on a vehicle for 21 powertrain zones and 42 receiving points located 7.5 m from the axis of the test track (a transfer function is measured twice for each source-receiver). The maximum observed uncertainty value was used. We have assumed that the measurement uncertainty related to the transfer function follows a uniform distribution between  $-1$  and  $+1$  dB (A).

**Tire/road contact noise  $L_{pc}$ :** the tire/road contact is the only source of noise that is measured directly as a contribution. The method used consists in measuring twice the contribution of tire/road contact for several vehicle speeds (from 30 to 80 km/h, with a step of 10 km/h). Then, a logarithmic regression (see Eq. (12)) allows us to obtain the empirical relationship that links the level of tire/road contact noise  $L_{pc}$  to the vehicle

speed  $V$  (see Figure 6). This formula allows us to obtain the nominal value of the tire/road contact noise level  $L_{pc}$ . In order to characterize the uncertainty associated with this parameter, 12 measurements were made on a vehicle driving at 50 km/h, then we calculated their mean and standard deviation. We observed that the mean value is close to the nominal value. This is why we assumed that the uncertainty follows a normal distribution with a standard deviation  $\sigma = 0.6$  dB (A).

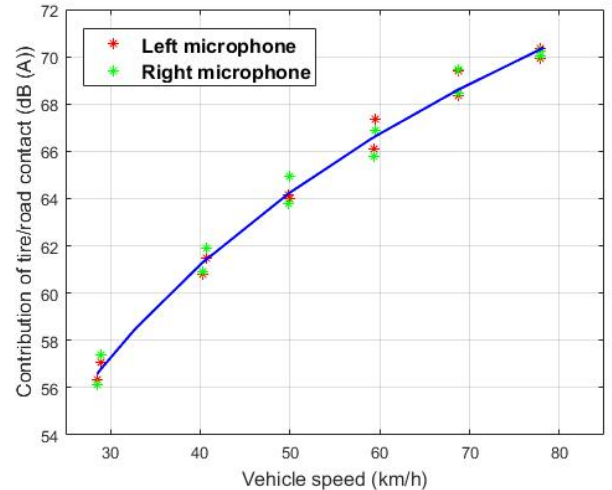


FIGURE 6: Example of the contribution of tire/road contact noise as a function of vehicle speed on the test track

**Wheel torque  $\tau_{tire}$ :** for configurations under full load acceleration, we add to the contribution of the tire at constant speed

a value related to the effect of the vehicle wheel torque  $\tau_{tire}$ . To quantify this uncertainty, the contribution of several tires is measured under full-load acceleration of the vehicle. It has been observed that, in the area of the track where the total contribution value is maximum (generally between +3 m and +5 m), the wheel torque effect adds 1 to 2.5 dB (A) to the tire's contribution at constant speed. It should be noted that this effect depends strongly on the acceleration of the vehicle, and may differ from one tire to another.

#### 4.1.2. Production variability

**The speed  $V_{mille}$ :** we have assumed that the production variability on the parameter  $V_{mille}$  is only related to the production dispersion on the circumference of the tire. The circumferential tolerance data of 70 different tires provided by the manufacturers are used to calculate the production uncertainty associated with this parameter. The maximum observed value is used. It corresponds to  $\pm 2.8\%$  of the nominal value of  $V_{mille}$ .

**Engine torque  $\tau$ :** assuming that all vehicles must be measured at the factory and that the value of the measured engine torque  $\tau$  must not exceed 5% of its maximum nominal value, we have decided to assign to this parameter a uniform distribution between -5 and 5 % of its nominal value.

In the absence of experimental data for the other parameters, we only used the expertise for the construction of the probability distributions (see Table 1).

#### 4.2. Propagation of uncertainties

After the quantification of uncertainties and the modelling of the input parameters of the synthesis model by random variables, it is necessary to propagate this uncertainty to characterize the variability of the outputs. To do this, we consider the input variables  $X$ , the output variables  $Y$  and  $\mathcal{M}$  represent the function of the model (the mathematical model, the numerical scheme and the calculation assumptions). We can write:

$$\mathcal{M} : \mathbb{R}^k \rightarrow \mathbb{R} \quad (19)$$

$$X \mapsto Y = \mathcal{M}(X) \quad (20)$$

where  $X = (X_1, X_2, \dots, X_k)$  is a random vector of  $k$  input variables. The  $Y$  outputs are therefore also random variables. The main objective of uncertainty propagation is to study the probability of the outputs of the model  $Y$ , namely their joint probability density function  $f_Y(y)$ . However, this probability function is difficult to calculate except in simple academic cases. To do this, the implementation of probability distributions in the model is done by approximation methods using random number generators. The most famous method is the Monte Carlo (MC) method [19, 20]. This method is often used since it provides

6. The notation  $X \sim \mathcal{N}(\mu, \sigma^2)$  is often used to describe a random variable  $X$  that follows a normal distribution of expectation  $\mu$  and standard deviation  $\sigma$ . The uniform law is often referred to as  $U(a,b)$ , where  $a$  and  $b$  represent the smallest and largest value that the random variable can take, respectively.

an efficient and robust methodology for generating model solution sets by sampling input parameters. However, this approach requires a large number of model evaluations.

In this paper, a method such as quasi-Monte Carlo [21, 22, 23] was used to accelerate the convergence of the Monte Carlo method (Sobol sequence [22]). Indeed, it reduces the cost of estimates by a factor of 10 [18]. This method, which is a deterministic version of Monte Carlo methods, defines deterministic sample sequences that have a lower discrepancy than random sequences, *i.e.* that it has a better distribution of samples in the parameter space. Its good occupancy of space makes this design of experiment very satisfying [24].

#### 4.3. Sensitivity analysis

After the quantification and propagation of uncertainties, comes the last step, which is sensitivity analysis. Its main objective is to study the impact of the variability of each input parameter on the model's output(s). It can determine the most influent parameters, those that do not influence the output, and those that interact within the model. The interest is undeniable, because the results of a sensitivity analysis can simplify the model or even improve its understanding. Finally and in general, sensitivity analysis is an aid to validate a calculation code, to orient research efforts, or to justify in terms of safety the dimensioning or modification of a system [24, 25, 26].

In our case, a linear relationship between the inputs and the outputs of the prediction model is verified (see Section 5.2.1). This allows us to define the Standardized Regression Coefficient  $SRC_i$ , where  $SRC_i^2 = S_i$  represents the sensitivity index that expresses the part of the variance of the  $Y$  output explained by the  $X_i$  parameter, with [18, 27, 28]:

$$SRC_i = \beta_i \sqrt{\frac{V(X_i)}{V(Y)}} \quad (21)$$

with  $\beta_i$  the regression coefficient of the  $X_i$  parameter.

When performing a linear regression between the output  $Y$  and the inputs  $X$ , it is important to calculate the coefficient of determination of the model  $R^2$ . It represents a quality criterion for model prediction, *i.e.* it provides a measure of how the linear regression model  $\widehat{Y}$  can reproduce the real output vector  $Y$ . It corresponds to the part of the variance of the model output  $Y$  explained by the linear regression. It is expressed by [24]:

$$R^2 = \frac{V(\widehat{Y})}{V(Y)} = \frac{\sum_{j=1}^N (\widehat{y}^{(j)} - \bar{y})^2}{\sum_{j=1}^N (y^{(j)} - \bar{y})^2} \quad (22)$$

where  $\bar{y}$  represents the mean of the sample  $\{y^{(1)}, \dots, y^{(N)}\}$ ,  $\widehat{y}^{(j)}$  represents the prediction of the linear model, and  $y^{(j)}$  represents the real output. Note that the closer the coefficient of determination  $R^2$  is to the unit, the better the performance of the regression model, and that the sum of the square of the  $SRC$  indices is  $R^2$ , with  $\sum_{i=1}^k SRC_i^2 = R^2$ .

It should be noticed that if two variables  $X_i$  and  $X_j$  are dependent, then the sensitivity index  $S_i$  no longer expresses only the sensitivity measure of  $Y$  to  $X_i$  but also a part of the influence of the parameter  $X_j$  on  $Y$ , with [29, 30, 31]:

$$S_i = S_i^c + S_i^u \quad (23)$$

where  $S_i^u$  and  $S_i^c$  are respectively the uncorrelated and correlated part of the sensitivity index  $S_i$ .

Some input parameters of the synthesis model can be highly correlated (see Figure 3). For example, the acoustic power of the sources  $W_{ac}$  depends on the rotational speed of the engine  $N_e$ , and therefore on the total mass  $m_g$ , the vehicle speed at 1000 rpm ( $V_{mille}$ ) and the engine torque in full load  $\tau$ . The contribution of tire/road contact noise  $L_{pc}$  is another example, since it depends on the vehicle speed  $V$ , and therefore on the three parameters mentioned above. It is then necessary to know how to interpret the sensitivity indices of these correlated input parameters. Indeed, the sensitivity index of the power of the sources  $W_{ac}$  and the contribution of the tire/road contact  $L_{pc}$  only measures the influence of these parameters on the model outputs:  $S_{(W_{ac}, L_{pc})} = S_{(W_{ac}, L_{pc})}^u$ . However, the sensitivity indices corresponding to  $m_g$ ,  $V_{mille}$  and  $\tau$  take into account, in addition to their influence on the model outputs, the influence of their correlation with the other parameters:  $S_{(m_g, V_{mille}, \tau)} = S_{(m_g, V_{mille}, \tau)}^u + S_{(m_g, V_{mille}, \tau)}^c$ .

Nevertheless, it should be noted that the parameters  $m_g$ ,  $V_{mille}$  and  $\tau$  have no direct influence on the noise levels  $L_{cr(n)}$ ,  $L_{wot(n)}$ ,  $L_{cr(n+1)}$  and  $L_{wot(n+1)}$ , i.e.  $S_{(m_g, V_{mille}, \tau)}^u = 0$ . Their sensitivity indices therefore correspond only to their correlation with the acoustic powers  $W_{ac}$  and the contribution of the tire/road contact  $L_{pc}$ :  $S_{(m_g, V_{mille}, \tau)} = S_{(m_g, V_{mille}, \tau)}^c$ . However, regarding the influence on the output  $L_{urban}$ , the term  $S_{(m_g, V_{mille}, \tau)}^u \neq 0$ , because the parameters  $m_g$ ,  $V_{mille}$ , and  $\tau$  are first used to determine the source power and the tire/road contact contribution, and then to calculate the vehicle accelerations  $a_{wot(n)}$  and  $a_{wot(n+1)}$  which are used to interpolate the noise levels  $L_{cr(n)}$ ,  $L_{wot(n)}$ ,  $L_{cr(n+1)}$  and  $L_{wot(n+1)}$  to obtain the noise level  $L_{urban}$  (see Section 2).

## 5. Results and discussion

### 5.1. Deterministic calculation

Before performing a calculation taking into account uncertainties, it is important to make a deterministic calculation to classify noise sources according to their influence on the noise level  $L_{urban}$ . Three vehicles with different power-to-mass ratios are selected: a B gasoline segment (entry-level), a B diesel segment (mid-range) and a D diesel segment (high-end). The choice of three vehicles with different power-to-mass ratios allows us to know the most influent parameters on the model's outputs, and to classify them by vehicle family. The results obtained are presented in Figure 7.

Note that two gear ratios are used to obtain the noise level  $L_{urban}$ , for all three vehicles. We can observe that the highest level  $L_{urban}$  corresponds to the entry-level vehicle. This is due to the contribution of the powertrain, which represents the most important source for this segment (approximately 60%). Tire/road contact noise is the second most important source for this segment, followed by other sources of noise, including exhaust line radiation, the intake and finally the exhaust tail. However, the contribution of the powertrain is becoming less and less important for both upper segments, which are dominated by tire/road contact noise. Indeed, the contribution of tire/road contact noise represents about 68% of the total contribution for the D diesel segment, while the contribution of the powertrain

represents only 26%.

### 5.2. Calculation under uncertainty

#### 5.2.1. Linearity of the model

Figure 8 represents the scatter plot of the output  $L_{urban}$  (in dB (A)) as a function of the 18 input parameters, after the propagation of the measurement uncertainty of the B diesel segment. First, we notice that the points are uniformly distributed in space: this confirms that there is no interaction effect between the parameters. We also observe a linear relationship between the inputs and the output of the model. We can also get an idea of the influent parameters from this figure, such as the level  $L_{urban}$  which increases linearly and considerably with the contribution of the tire/road contact at constant speed.

Since our model is simple (no interaction, and linear effect also verified for other vehicles), we will use, in the following paper, quasi-Monte Carlo methods to propagate uncertainty and linear regression to estimate sensitivity indices. The sensitivity can then simply be quantified by the *SRC* index (see Eq. (21)). This allows us to considerably reduce the number of simulations, and thus reduce calculation time when introducing production variability. However, it should be noticed that, in our study, all vehicle types were, as in most cases, in a situation where none of the gear ratios allowed to approach the reference acceleration for the wide-open-throttle test  $a_{wot ref}$ . Two gear ratios are then used to frame this reference acceleration and therefore estimate the value  $L_{urban}$  (see Section 5.1). On the other hand, in some situations, variations related to the engine torque  $\tau$ , the  $V_{mille}$ , as well as the vehicle mass  $m$  and the driver mass  $m_d$  can modify the vehicle accelerations and therefore the model's behaviour. Therefore, depending on the value of the random draw on the input parameters, the model may sometimes use a single or two gear ratios to estimate the value  $L_{urban}$ . In this case, the model becomes discontinuous and the estimation of the Sobol indices is necessary to have unbiased sensitivity indices [32]. Another solution is to separate and study the two configurations separately. However, this separation of samples creates dependency between input parameters, which makes the analysis more complex.

In order to introduce production variability, we generated a quasi-Monte Carlo draw of  $N_{PU} = 1024$  samples from the input parameters characterizing vehicles of the same technical definition produced with the same industrial tools. For each vehicle,  $N_{MU} = 1024$  draws are generated from the measurement uncertainty related to its parameters. A linear regression between each output of the model and the 18 input parameters is then performed, and the coefficients of determination are calculated. We noted that  $R_p^2 = 0.99 \approx 1$ ,  $R_M^2 = 0.99 \approx 1$  for the 5 outputs of the model, where  $R_p^2$  represents the coefficient of determination for the production variability and  $R_M^2$  the coefficient of determination for the measurement uncertainty. This means that the model's linearity assumption is indeed acceptable, and that the *SRC* sensitivity indices can be used. The sensitivity of each output is then studied by calculating sensitivity indices *SRC<sub>m</sub>* for measurement uncertainty, and sensitivity indices *SRC<sub>p</sub>* for production variability. In Figure 9, the results of the *SRC<sub>m</sub>*<sup>2</sup> in-

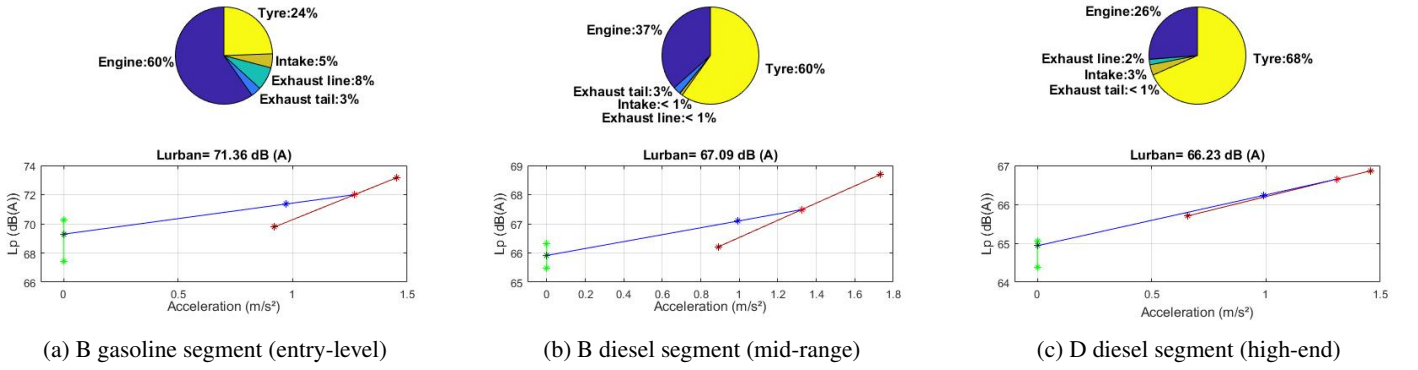


FIGURE 7: Results of the deterministic calculation performed on three different vehicle types

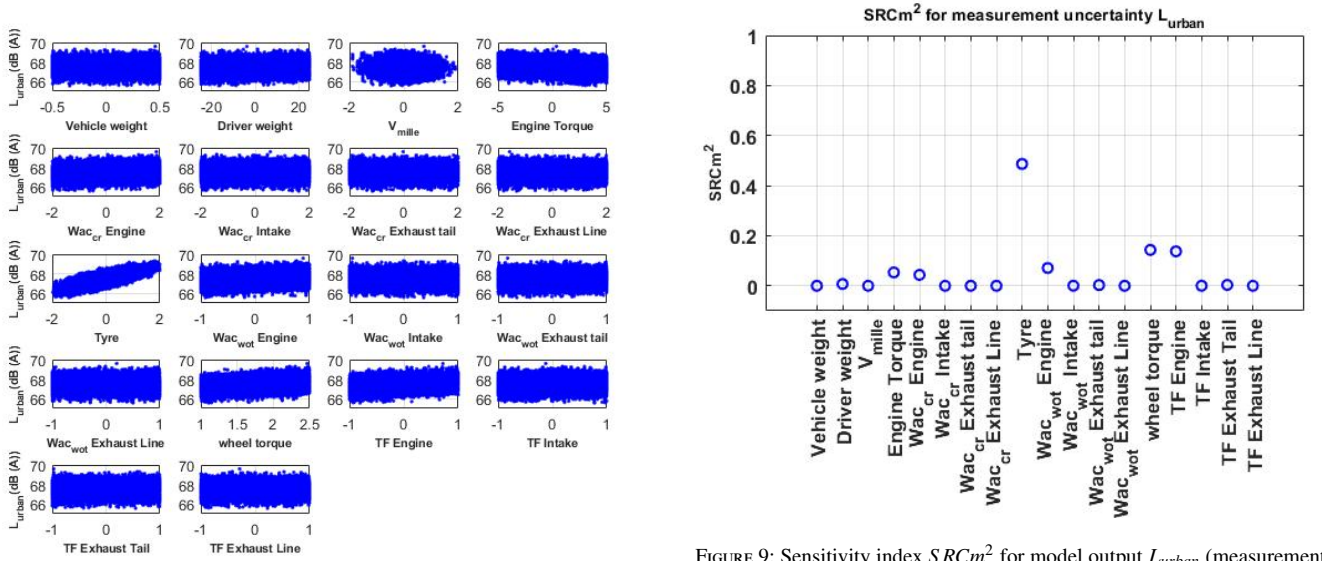


FIGURE 8: Output scatterplot  $L_{urban}$  as a function of the 18 input parameters of the model (measurement uncertainty, B diesel segment)

trices are presented. We can see that  $\sum_{i=1}^k SRCm_i^2 = 0.96 \approx R_M^2$  ( $k$  is the number of parameters). This confirms the previous observations, *i.e.* the model is linear and without interactions between the parameters.

### 5.2.2. Results of measurement uncertainty

The sensitivity indices corresponding to the measurement uncertainty  $SRCm_i$  for the B diesel segment are presented in Figure 10, for the 4 outputs of the model  $L_{cr(n)}$ ,  $L_{wot(n)}$ ,  $L_{cr(n+1)}$  and  $L_{wot(n+1)}$ . First, we notice that the indices are different from one configuration to another. For the constant speed run with gear ratio ( $n$ ) (*i.e.*  $L_{cr(n)}$ ), the power and transfer function of the powertrain and the contribution of the tire/road contact are the most influent parameters. Concerning the constant speed run with gear ratio ( $n+1$ ) (*i.e.*  $L_{cr(n+1)}$ ), it is always the same parameters that are influent, with slightly different amplitudes. Indeed, the run with a higher gear ratio reduces the powertrain's

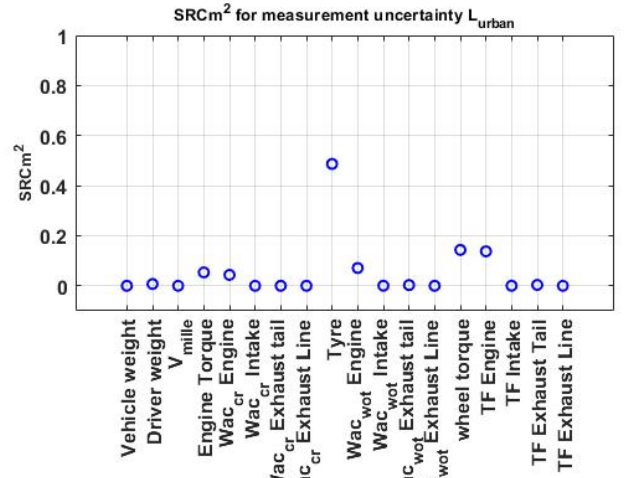


FIGURE 9: Sensitivity index  $SRCm^2$  for model output  $L_{urban}$  (measurement uncertainty, B diesel segment)

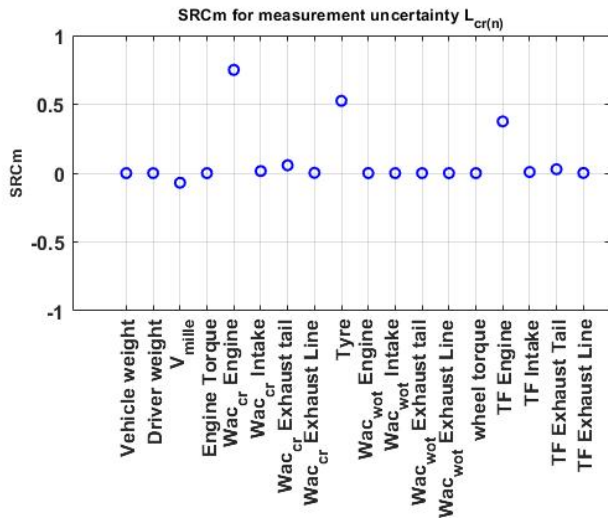
contribution, and therefore its sensitivity index. For runs under full load ( $L_{wot(n)}$  and  $L_{wot(n+1)}$ ), the parameter related to the effect of the wheel torque appears systematically, in addition to the parameters mentioned above, as an important parameter.

To compare the three vehicle types, the sensitivity indices  $SRCm_i$  corresponding to the output  $L_{urban}$  are presented in Figure 11. The results become different from one vehicle type to another. Indeed, the power and transfer function of the powertrain are influent parameters for the B segment gasoline, which corresponds to a small, low-power vehicle (entry-level vehicle). This influence becomes more and more negligible for other segments. For example, for the D diesel segment, the influence of powertrain noise is negligible, the output  $L_{urban}$  is then dominated by variations related to the contribution of the tire/road contact  $L_{pc}$ , as well as the effect of the wheel torque  $\tau_{tire}$ . Moreover, for the B gasoline segment, the engine torque  $\tau$  seems to have a great influence. This effect has also been observed on another vehicle in the same segment, which is not presented in this paper. Indeed, this parameter does not directly influence

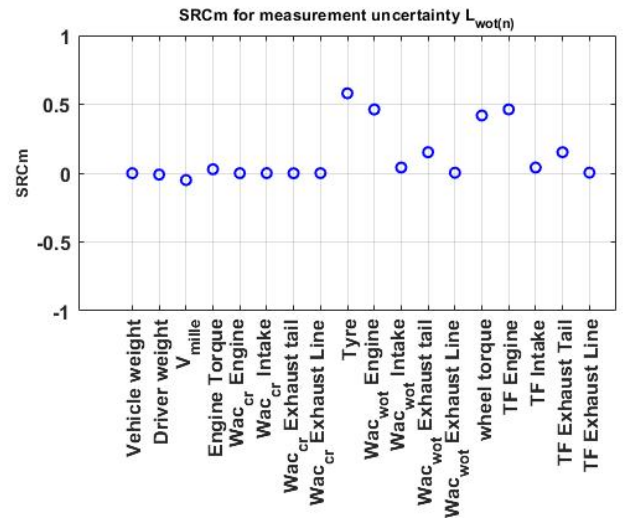
the estimated noise at each run, but it can have an influence on the acceleration of the vehicle, and therefore an influence on the value  $L_{urban}$  when interpolating. Therefore, the terms  $S_m^u$ ,  $S_{m_d}^u$ ,  $S_{V_{mille}}^u$  and  $S_\tau^u$  may be different from zero when it is about influencing the  $L_{urban}$  output. In addition, the sensitivity index related to the engine torque  $\tau$  is negative, which means that the noise level  $L_{urban}$  is inversely proportional to this parameter, and therefore to the acceleration of the vehicle. This parameter can therefore be very important, especially for small, low-power vehicles (entry-level vehicles, see Figure 11a). However, it is less important for the B diesel segment, and even less important for the D diesel segment (high-end vehicle). For example, today we know that pre-accelerating on the track allows some vehicles, especially those equipped with turbochargers, to accelerate better and therefore to decrease the  $L_{urban}$  level. This difference, observed between the three vehicles, of the influence of the engine torque  $\tau$  on the level  $L_{urban}$ , can be explained by the interpolation diagrams (see Figure 12). Indeed, we notice a gap in the noise levels  $L_{wot(n)}$  and  $L_{wot(n+1)}$  between the two gear ratios (n) and (n+1) for the B gasoline segment (see Figure 12a). This is why small variations in acceleration (which depends on the engine torque  $\tau$ ) can cause a large dispersion over the  $L_{urban}$  during interpolation. However, for the D diesel segment,  $L_{wot(n)}$  and  $L_{wot(n+1)}$  are of the same level (see Figure 12c). As a result, the influence of engine torque variations  $\tau$  is close to zero. We observe exactly the same effect with respect to the driver's mass  $m_d$ . Nevertheless, the value of sensitivity index linked to this parameter is positive (see Figure 11a). Indeed, and contrary to engine torque, an increase in mass reduces the vehicle's acceleration. However, this sensitivity index remains negligible compared to the sensitivity indices of the other parameters.

### 5.2.3. Results of production variability

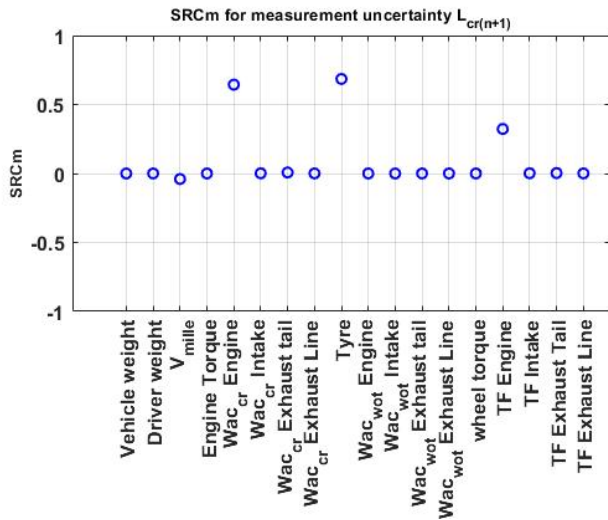
The sensitivity indices corresponding to the production uncertainty  $SRCp_i$  for the B diesel segment are presented in Figure 13, for the 4 outputs of the model  $L_{cr(n)}$ ,  $L_{wot(n)}$ ,  $L_{cr(n+1)}$  and  $L_{wot(n+1)}$ . The influent parameters are the same as those corresponding to the measurement uncertainty. However, their amplitude differs because the ranges of the used variabilities are uneven. The main difference is in the sensitivity index associated with the  $V_{mille}$  parameter. The variability range corresponding to 2.8% on this parameter can have a considerable influence on the 4 outputs of the model  $L_{cr(n)}$ ,  $L_{wot(n)}$ ,  $L_{cr(n+1)}$  and  $L_{wot(n+1)}$ ; indeed, this influence is due only to the correlation between the parameter  $V_{mille}$  with the acoustic powers  $Wac$  and the contribution of the tire/road contact  $L_{pc}$ , *i.e.*  $S_{V_{mille}} = S_{V_{mille}}^c$ . It should also be noticed that this sensitivity index is negative; this implies that the 4 outputs of the model are inversely proportional to the parameter  $V_{mille}$ . The tolerance on the circumference of the tire is then a parameter to be taken into account before performing a study on a vehicle, in particular for the 4 noise levels  $L_{cr(n)}$ ,  $L_{wot(n)}$ ,  $L_{cr(n+1)}$  and  $L_{wot(n+1)}$ . Nevertheless, considering the output  $L_{urban}$ , the sensitivity index related to the production uncertainty on the  $V_{mille}$  parameter becomes negligible in comparison with the others (see Figure 14).



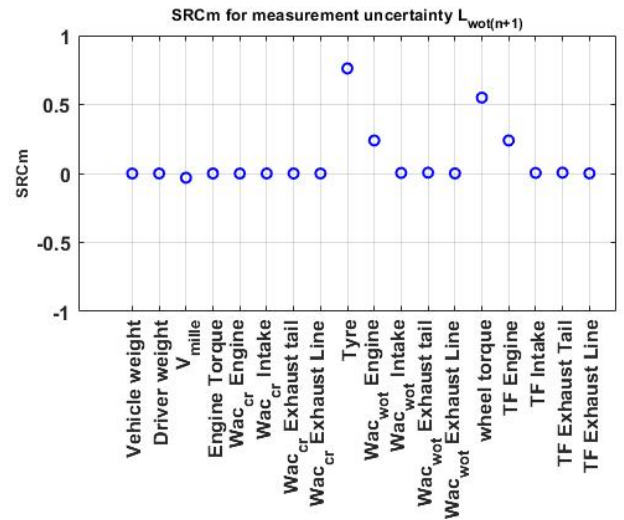
(a) Constant speed gear n:  $L_{cr(n)}$



(b) Full load gear n:  $L_{wot(n)}$

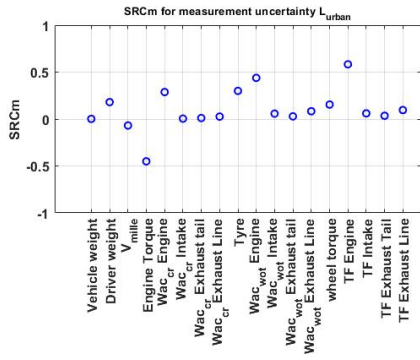


(c) Constant speed gear n+1:  $L_{cr(n+1)}$

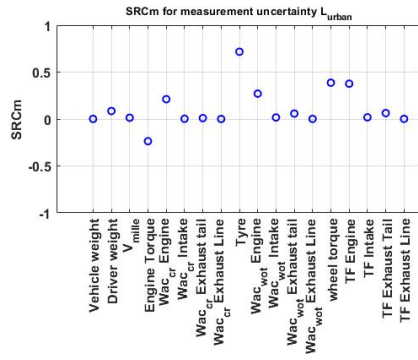


(d) Full load gear n+1:  $L_{wot(n+1)}$

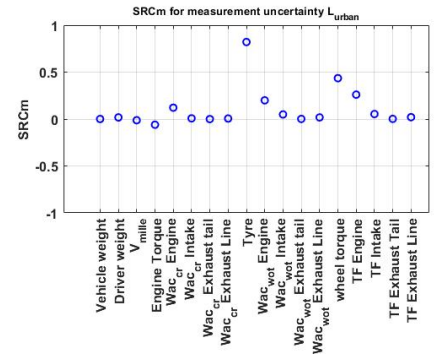
FIGURE 10: Sensitivity indices  $SRCm$  corresponding to the measurement uncertainty for the B diesel segment for the 4 outputs of the model  $L_{cr(n)}$ ,  $L_{wot(n)}$ ,  $L_{cr(n+1)}$  and  $L_{wot(n+1)}$ .



(a) B gasoline

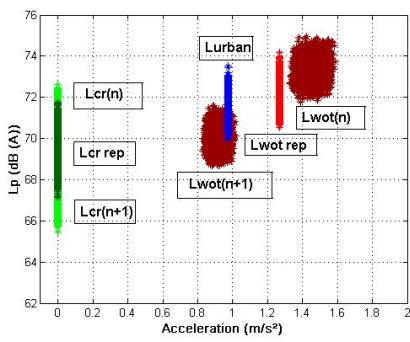


(b) B diesel

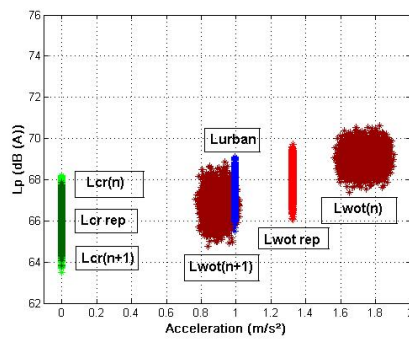


(c) D diesel

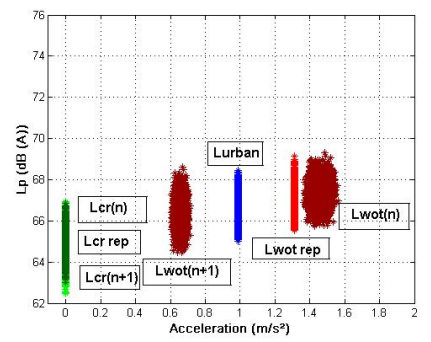
FIGURE 11: Sensitivity indices  $SRC_m$  corresponding to the measurement uncertainty on the output  $L_{urban}$  for the three vehicle types



(a) B gasoline

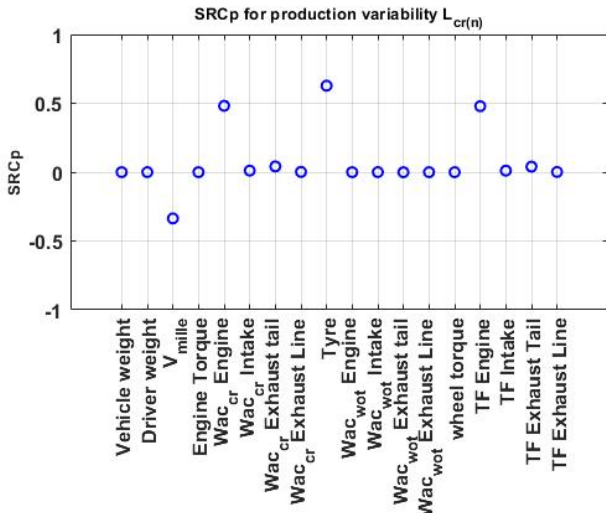


(b) B diesel

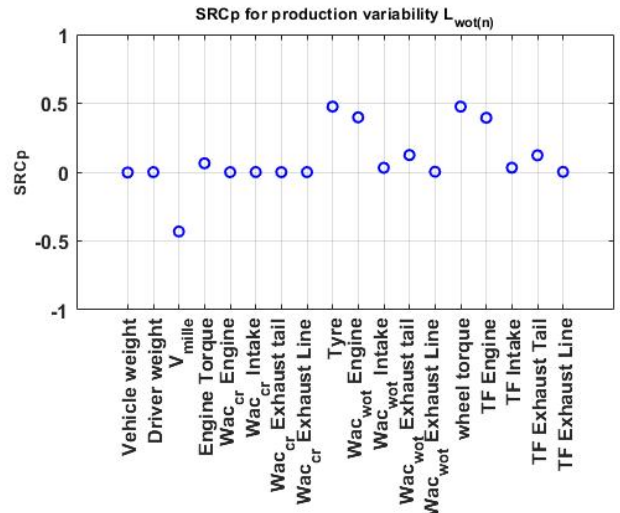


(c) D diesel

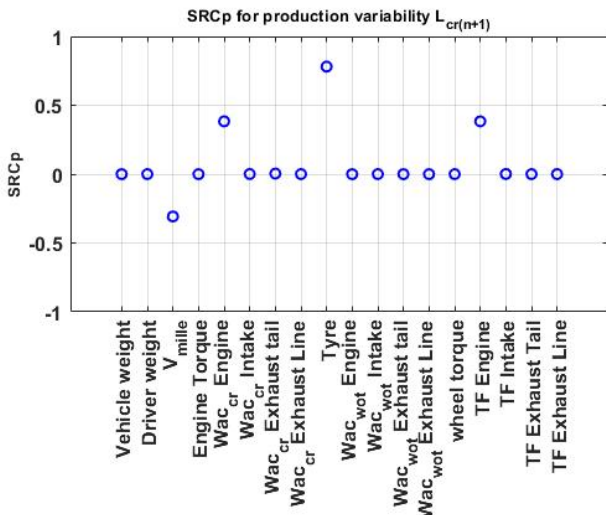
FIGURE 12: Interpolation diagram to calculate the noise level  $L_{urban}$  for the three vehicle types



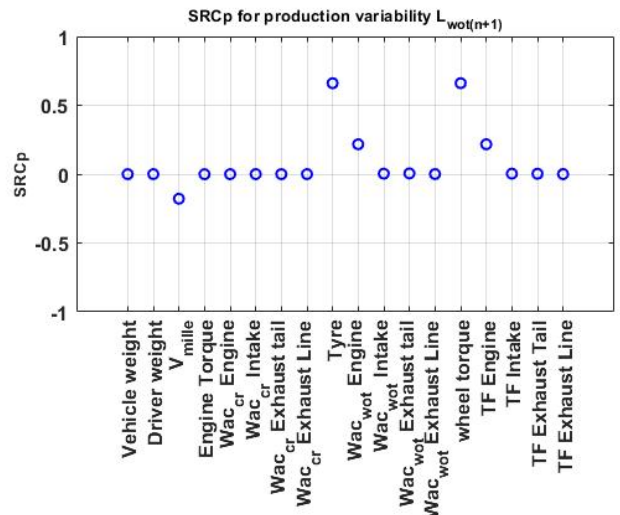
(a) Constant speed gear  $n$ :  $L_{cr(n)}$



(b) Full load gear  $n$ :  $L_{wot(n)}$

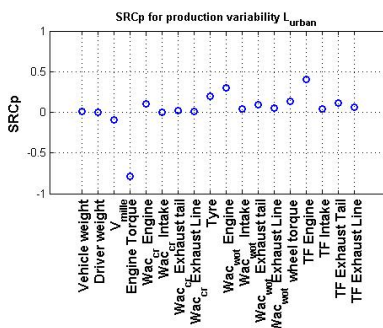


(c) Constant speed gear  $n+1$ :  $L_{cr(n+1)}$

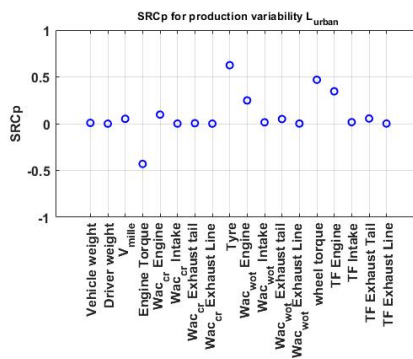


(d) Full load gear  $n+1$ :  $L_{wot(n+1)}$

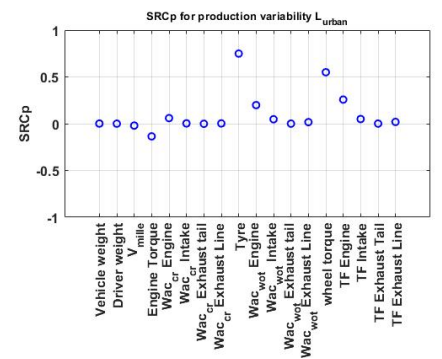
FIGURE 13: Sensitivity indices  $SRCp$  corresponding to the production variability for the B diesel segment for the 4 outputs of the model  $L_{cr(n)}$ ,  $L_{wot(n)}$ ,  $L_{cr(n+1)}$  and  $L_{wot(n+1)}$ .



(a) B gasoline



(b) B diesel



(c) D diesel

FIGURE 14: Sensitivity indices  $SRCp$  corresponding to the production variability on the output  $L_{urban}$  for the three vehicles

## 6. Conclusion and perspectives

This paper addresses the problem of model construction for the simulation of vehicle pass-by noise in order to predict and evaluate accurately the noise emissions earlier in the vehicle development cycle, *i.e.* before the industrialization stage. The application of sensitivity analysis and propagation of uncertainty methods to vehicle pass-by noise prediction model is presented. The study is carried out on three vehicle types with different power-to-mass ratios. The input parameters of the model are considered uncertain. This is why a quantification of uncertainties is first carried out by distinguishing between *measurement uncertainty* and *production variability*. These uncertainties are then propagated in the model using a quasi-Monte Carlo method. Finally, a sensitivity analysis study is carried out to study the impact of the variability of the input parameters on the variability of the noise levels at the output of the model. Influential parameters have been identified and classified for each vehicle family.

The work presented in this paper offers many perspectives. First, a sensitivity analysis study was carried out and the influential parameters were identified. It would then be more relevant to focus on the uncertainty of the most influential input parameters in order to improve the prediction of the synthesis model.

The effect of the wheel torque  $\tau_{tire}$  is also an important parameter. However, today, this parameter is poorly characterized. It is therefore necessary to further investigate this subject and develop precise models to characterize the contribution of tire/road contact noise, which may depend on the speed of the vehicle but also on its acceleration.

In order to evaluate the accuracy and robustness of the proposed model, it would be interesting in assessing the repeatability and the reproducibility of the pass-by noise of several vehicles with the same technical definition and produced with the same tools.

Moreover, the prediction capacities of the model could be improved by using a better description, for example by modifying the geometric and frequency refinement of the noise sources. For example, the powertrain could be spatially divided into six sides or several zones with a frequency dependence given by third octave bands or narrow bands (instead of overall value). To go even further, after passing in narrow bands, we can consider a correlation between the exhaust tail noise and the intake noise. Indeed, the intake and exhaust systems are two significant sources in the calculation of external noise, due to air pressure pulsations when opening and closing the valves. At low frequencies, both noise sources are loaded with harmonics whose main components are directly related to the engine's rotational speed. This is why these two sources can be assumed to be correlated but only up to a specific frequency. The temperature of the sources could also be an important parameter. Indeed, the acoustic power of the sources is highly dependent on temperature, which unfortunately is not taken into account in the current model.

However, this simple approach of increasing the number of

model parameters can lead to the phenomenon of overfitting. Generally, if the prediction error decreases at first, it increases above a certain limit when the number of parameters is increased [33, 34, 35]. It will then be necessary to address the problem of model construction from the point of view of the trade-off between the robustness and precision of these models.

## References

- [1] United Nations Economic Commission for Europe, Addendum 50 : Regulation No. 51 Revision 3. Uniform provisions concerning the approval of motor vehicles having at least four wheels with regard to their sound emissions (2016).
- [2] United Nations Economic Commission for Europe, Addendum 50 : Regulation No. 51 Revision 2. Uniform provisions concerning the approval of motor vehicles having at least four wheels with regard to their sound emissions (2011).
- [3] C. Locqueteau, J. Salem, Point of view of automotive OEM for new passby noise regulation R51-03 : challenges and new deployment, in : Automotive and Railway Comfort, SIA, 2012.
- [4] L. Pardo, S. Ficheux, Exterior pass-by noise regulation - Monitoring database and impact assessment, in : Automotive and Railway Comfort, SIA, 2012.
- [5] International Organization for Standardization, ISO 362-1 : Measurement of noise emitted by accelerating road vehicles — Engineering method — Part 1 : M and N categories (2015).
- [6] International Organization for Standardization, ISO 362 : Acoustics - Measurement of noise emitted by accelerating road vehicles - Engineering method (1998).
- [7] International Organization for Standardization, ISO 10844 : Acoustique - Spécification des surfaces d'essai pour le mesurage du bruit émis par les véhicules routiers et leurs pneumatiques (2014).
- [8] J. Huijssen, R. Hallez, B. Pluymers, W. Desmet, A synthesis procedure for pass-by noise of automotive vehicles employing numerically evaluated source-receiver transfer functions, Journal of Sound and Vibration 332 (2013) 3790–3802.
- [9] M. Braun, S. Walsh, J. Horner, R. Chuter, Noise source characteristics in the ISO 362 vehicle pass-by noise test : Literature review, Applied Acoustics 74 (2013) 1241–1265.
- [10] M. Braun, Sound source contributions for the prediction of vehicle pass-by noise, Ph.D. thesis, Loughborough University (2014).
- [11] P. Van de Pongsele, H. Van der Auweraer, K. Janssens, Source-Transfer-Receiver approaches : a review of methods, in : International Conference on Noise and Vibration Engineering, USD, ISMA, 2012.
- [12] K. Janssens, F. Bianciardi, L. Britte, P. Van de Pongsele, H. Van der Auweraer, Pass-by noise engineering : a review of different transfer path analysis techniques, in : International Conference on Noise and Vibration Engineering, USD, ISMA, 2014.
- [13] U. Sandberg, J. Ejsmont, Tyre/road noise reference book, Informex, 2002.
- [14] E. DE Recquigny, N. Devictor, S. Tarantola, Uncertainty in industrial practice, Wiley, 2008.
- [15] E. T. Jaynes, Information theory and statistical mechanics, Phys. Rev. 106 (1957) 620–630. doi : 10.1103/PhysRev.106.620.
- [16] J. Kapur, H. Kesavan, Entropy optimization principles with applications, Academic Press, 1992.
- [17] C. Shannon, A mathematical theory of communication 27 (1948) 379–423, 623–656.
- [18] A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, S. Tarantola, Global Sensitivity Analysis - The primer, Wiley, 2008.
- [19] J. M. Hammersley, D. C. Handscomb, Monte Carlo Methods, Monographs on Statistics and Applied Probability, Springer Netherlands, 1964.
- [20] C. Robert, G. Casella, Monte Carlo Statistical Methods, Springer, 1999.
- [21] P. Hellekalek, G. Larcher, Random and Quasi-Random Point Sets, Springer-Verlag New York, 1998.
- [22] P. Bratley, B. L. Fox, Algorithm 659 : Implementing sobol's quasirandom sequence generator, ACM Trans. Math. Softw. 14 (1) (1988) 88–100. doi : 10.1145/42288.214372.
- [23] J. H. Halton, On the efficiency of certain quasi-random sequences of points in evaluating multi-dimensional integrals, Numer. Math. 2 (1) (1960) 84–90. doi : 10.1007/BF01386213.

- [24] B. Iooss, P. Lemaître, A review on global sensitivity analysis methods, in : C. Meloni, G. Dellino (Eds.), *Uncertainty management in Simulation-Optimization of Complex Systems : Algorithms and Applications*, Springer, 2015.
- [25] J. Jacques, *Contributions à l'analyse de sensibilité et à l'analyse discriminante généralisée*, Theses, Université Joseph-Fourier - Grenoble I (Dec. 2005).
- [26] B. Iooss, Revue sur l'analyse de sensibilité globale de modèles numériques, *Journal de la Societe Française de Statistique* 152 (1) (2011) 1–23.
- [27] A. Saltelli, K. Chan, E. Scott, *Sensitivity Analysis*, Wiley, 2000.
- [28] A. Saltelli, S. Tarantola, F. Campolongo, M. Ratto, *Sensitivity analysis in practice : A guide to assessing scientific models*, Wiley, 2004.
- [29] A. Saltelli, T. S, On the relative importance of input factors in mathematical models : Safety assessment for nuclear waste disposal 97 (2002) 702–709.
- [30] T. A. Mara, S. Tarantola, Variance-based sensitivity indices for models with dependent inputs, *Reliability Engineering and System Safety* 107 (2012) 115 – 121. doi : 10.1016/j.ress.2011.08.008.
- [31] M. D. McKay, Nonparametric variance-based methods of assessing uncertainty importance, *Reliability Engineering & System Safety* 57 (3) (1997) 267 – 279. doi : 10.1016/S0951-8320(97)00039-2.
- [32] I. M. Sobol, Sensitivity estimates for nonlinear mathematical models 1 (1993) 407 – 414.
- [33] K. P. Burnham, D. R. Anderson, *Multimodel Inference : Understanding AIC and BIC in Model Selection*, *Sociological Methods & Research* 33 (2) (2004) 261–304. doi : 10.1177/0049124104268644.
- [34] K. Burnham, D. Anderson, *Model Selection and Multimodel Inference : A Practical Information-Theoretic Approach*, Springer-Verlag New York, 2002.
- [35] D. J. MacKay, Bayesian interpolation, *Neural Computation* 4 (1991) 415–447.

## Nomenclature

$\bar{y}$	Mean of the samples	$L_{pc}$	Overall noise level of the tire (in $dB(A)$ )
$\beta_i$	Regression coefficient of the $X_i$ parameter	$L_{wot(n)}$	Sound pressure level corresponding to the full load acceleration of the vehicle for the gear ratio (n) (in $dB(A)$ )
$\dot{Q}_i$	Volume acceleration flow rate corresponding to the source $i$ (in $m^3/s^2$ )	$L_{wot(n+1)}$	Sound pressure level corresponding to the full load acceleration of the vehicle for the gear ratio (n+1) (in $dB(A)$ )
$\mu$	Expectation of the distribution	$L_{wot\ rep}$	The linear interpolation between the two sound pressure levels of the gear ratio (n) and (n+1) under full load acceleration (in $dB(A)$ )
$\omega$	Angular velocity (in $rad/s$ )	$m$	Vehicle mass (in $kg$ )
$\omega_e$	Engine rotation speed (in $rad/s$ )	$m_d$	Driver's mass (in $kg$ )
$\rho$	Density of air (in $kg.m^{-3}$ )	$m_g$	Total mass (in $kg$ )
$\sigma$	Standard deviation	$m_{ro}$	Mass of vehicle in running order (in $kg$ )
$\tau$	Engine torque (in $Nm$ )	$N_e$	Engine rotation speed (in $rpm$ )
$\tau_{tire}$	Wheel torque (in $Nm$ )	$N_{MU} =$	Number of samples of measurement uncertainty
$\widehat{y}$	Prediction of the linear model	$N_{PU}$	Number of samples of production variability
$A_p$	Constant that depends on the tire and the vehicle's position on the track (in $dB(A)$ )	$P_j$	Sound pressure level at the measurement point $j$ (in $Pa$ )
$a_{urban}$	Target acceleration : the typical acceleration in an urban environment (in $m/s^2$ )	$P_n$	Power of the vehicle (in $kW$ )
$a_{wot(n)}$	Full load acceleration of the vehicle for the gear ratio (n) (in $m/s^2$ )	$PMR$	Power to Mass Ratio index
$a_{wot(n+1)}$	Full load acceleration of the vehicle for the gear ratio (n+1) (in $m/s^2$ )	$R^2$	Coefficient of determination
$a_{wot\ ref}$	Reference acceleration for the wide-open-throttle test : the acceleration required during the full load acceleration test (in $m/s^2$ )	$R_M^2$	Coefficient of determination for the measurement uncertainty
$B_p$	Constant that depends on the tire and the vehicle's position on the track (in $dB(A)$ )	$R_P^2$	Coefficient of determination for the production variability
$c$	Velocity of sound (in $m/s$ )	$R_r$	Rolling resistance force (in $N/t$ )
$f_Y(y)$	Joint probability density function of the output variables	$S_i$	Sensitivity index of the parameter $i$
$F_{aero}$	Aerodynamic force (in $N$ )	$S_i^c$	Correlated part of the sensitivity index $S_i$
$F_{bearing}$	Force related to bearing friction (in $N$ )	$S_i^u$	Uncorrelated part of the sensitivity index $S_i$
$F_{brake}$	Force related to brake friction (in $N$ )	$SRC$	Standardized Regression Coefficient
$F_{d(n)}$	Driving force developed by the vehicle at 50 $km/h$ for the gear ratio (n) (in $N$ )	$SRC_m$	Standardized Regression Coefficient for measurement uncertainty
$F_r$	Resistive force at 50 $km/h$ (in $N$ )	$SRC_p$	Standardized Regression Coefficient for production variability
$K$	Gear ratio weighting factor	$T_y$	Transmission efficiency (in %)
$k$	Number of sources	$TF_{ij}$	Transfer function between the source $i$ and the measurement point $j$ (in $Pa.m^{-3}.s^2$ )
$K_p$	The partial power factor	$V$	Vehicle speed (in $km/h$ )
$L_{crs(n)}$	Sound pressure level at a constant speed of 50 $km/h$ for the gear ratio (n) (in $dB(A)$ )	$V(.)$	Variance of a random variable
$L_{crs(n+1)}$	Sound pressure level at a constant speed of 50 $km/h$ for the gear ratio (n+1) (in $dB(A)$ )	$V_0$	Vehicle speed on line PP' (in $km/h$ )
$L_{crs\ rep}$	The linear interpolation between the two sound pressure levels of the gear ratio (n) and (n+1) at a constant speed of 50 $km/h$ (in $dB(A)$ )	$V_{mille(n)}$	Vehicle speed when the engine speed $N_e = 1000\ rpm$ (in $km/h$ )
		$Wac$	Acoustic power of a source (in $dBW$ )

$Wac_{cr}$	Acoustic power of a source at a constant speed of 50 km/h (in dBW)
$Wac_{wot}$	Acoustic power of a source under full load acceleration (in dBW)
$X$	Random vector of input variables
$X_v$	Vehicle position on the track (in $m$ )
$X_{v0}$	Vehicle position on line PP' (in $m$ )
$Y$	Random vector of output variables
$y$	Real output of the model
$L_{urban}$	Pass-by noise level under partial load (in $dB(A)$ )