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# Acoustic response variability in automotive vehicles

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## Abstract

A statistical analysis of a series of measurements of the audio-frequency response of a large set of automotive vehicles is presented: a small hatchback model with both a three-door (411 vehicles) and five-door (403 vehicles) derivative and a mid-sized family five-door car (316 vehicles). The sets included vehicles of various specifications, engines, gearboxes, interior trim, wheels and tyres. The tests were performed in a hemianechoic chamber with the temperature and humidity recorded. Two tests were performed on each vehicle and the interior cabin noise measured. In the first, the excitation was acoustically induced by sets of external loudspeakers. In the second test, predominantly structure-borne noise was induced by running the vehicle at a steady speed on a rough roller.

For both types of excitation, it is seen that the effects of temperature are small, indicating that manufacturing variability is larger than that due to temperature for the tests conducted. It is also observed that there are no significant outlying vehicles, i.e. there are at most only a few vehicles that consistently have the lowest or highest noise levels over the whole spectrum. For the acoustically excited tests, measured 1/3-octave noise reduction levels typically have a spread of 5 dB or so and the normalised standard deviation of the linear data is typically 0.1 or higher. Regarding the statistical distribution of the linear data, a lognormal distribution is a somewhat better fit than a Gaussian distribution for lower 1/3-octave bands, while the reverse is true at higher frequencies. For the distribution of the overall linear levels, a Gaussian distribution is generally the most representative. As a simple description of the response variability, it is sufficient for this series of measurements to assume that the acoustically induced airborne cabin noise is best described by a Gaussian distribution with a normalised standard deviation between 0.09 and 0.145.

There is generally considerable variability in the roller-induced noise, with individual 1/3-octave levels varying by typically 15 dB or so and with the normalised standard deviation being in the range 0.2–0.35 or more. These levels are strongly affected by wheel rim and tyre constructions. For vehicles with nominally identical wheel rims and tyres, the normalised standard deviation for 1/3-octave levels in the frequency range 40–600 Hz is 0.2 or so. The distribution of the linear roller-induced noise level in each 1/3-octave frequency band is well described by a lognormal distribution as is the overall level. As a simple description of the response variability, it is sufficient for this series of measurements to assume that the roller-induced road noise is best described by a lognormal distribution with a normalised standard deviation of 0.2 or so, but that this can be significantly affected by the tyre and rim type, especially at lower frequencies.

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## 1. Introduction

It is widely recognised that manufacturing variability is inevitable and causes consequent variability in the noise and vibration responses of structures, even though they nominally have the same physical and geometric properties. One example, and perhaps the most important, is the automotive industry, where vehicles have responses in the audio-frequency range, which can vary significantly from one vehicle to the next. The variability arises from the accumulation of effects such as dimensional tolerances, joint stiffnesses, material properties and so on, not to mention the fact that there are commonly minor differences in vehicle specifications and trim levels during the course of the manufacturing life-cycle of a particular model.

The engineer has a desire to quantify this variability and to produce robust designs to ensure that not only the ensemble mean response is within design limits but also that the response statistics such as standard deviation, percentiles and confidence limits, are also acceptable.

One approach might be to attempt to quantify the statistics of the individual components of a product and propagate these through the analysis to predict the response statistics. While this is desirable in the design stage, it might be a daunting task. More frequently, end-of-line response measurements might be taken on a number of structures, as part of a quality control or monitoring approach perhaps, to estimate response statistics. Relatively few samples need to be tested to estimate the mean response, more to estimate variance and substantially more to estimate distributions. The latter are important because the tails of the distribution represent those outlying vehicles whose response might be unacceptable. If the distribution is known, however, the percentiles can be readily estimated from the mean and variance.

With regard to the audio-frequency response of vehicles, there is relatively little published data to indicate what are typical levels of variability and less to indicate typical distributions, although Gaussian and lognormal are perhaps likely contenders. This paper contributes to this subject, presenting response statistics for very large data sets.

Wood and Joachim [1,2] presented results for measured interior noise levels and structural and acoustic transfer functions for an ensemble of six vehicles, observing variability as high as 15 dB. Benedict et al. [3] presented measurements of acoustic transfer functions for 10 nominally identical vehicles. Variability was again up to 15 dB while test variability—estimated by repeating measurements of a single vehicle 8 times—was about 2 dB.

In a much larger study, Bernhard and Kompella [4] investigated the variability in the structure-borne and airborne frequency response functions (FRFs) for two different Isuzu car models, namely the Rodeo, of which 98 nominally identical vehicles were measured, and the Isuzu Pick-up of which there were 57. The authors subsequently reported further statistical analysis in Refs. [5,6] and a statistical analysis of the response distributions for these data sets was given in Refs. [7,8]. In Ref. [4], structure-borne FRFs were measured from the front left wheel hub to interior microphones at the driver's and front passenger's ear locations and airborne FRFs were measured from a reference exterior microphone located outside the vehicle at the front left wheel position to interior microphones at the same positions with a loudspeaker near to the exterior microphone used as the acoustic source. A reference vehicle of each type was tested repeatedly to assess the measurement process variability. The temperature and humidity were monitored for each test. As the vehicles were tested outside, there were significant temperature fluctuations (20.1–47.1 °C) due to the weather.

The ranges of the airborne FRFs were 21.8 dB (Pickup vehicle set) and 23.3 dB (Rodeo), and those of the structure-borne FRFs 23.4 dB (Pick-up) and 26.5 dB (Rodeo). The variability increased with increasing frequency. In Refs. [7,8], it was seen that, in general, a Gaussian distribution was a reasonable fit to the linear response data over most of the frequency range, although overall a lognormal distribution was a somewhat better fit.

Finally in Ref. [9], Lionnet et al. described a hierarchical approach that attempts to subdivide the sources of variability in a systematic manner. Measurements were taken over a wide range of operating conditions, and in particular temperature, and the difference between intra-variability (that in a single vehicle due to changes in operating conditions, etc.) and inter-variability (that due to manufacturing variability that produces different responses in different vehicle under the same operating conditions). Measurements on nine vehicles indicated variability of up to 10 dB in booming noise and 8 dB or so for a structural acoustic transfer function.

This paper presents a study of the statistics of the audio-frequency response of a very large vehicle data set. Measurements were taken in a hemianechoic chamber on two sets of cars, totalling 1130 vehicles, as an end-of-line production assessment, not primarily for variability investigations. There were various vehicle specifications and body types, which were recorded for each test, as were the test temperature and humidity. Two tests were performed on each vehicle. In the first, the excitation was acoustically introduced by sets of loudspeakers and 1/3-octave noise levels inside the vehicle cabin were recorded in the frequency range from 50 Hz to 10 kHz, giving 648 measurements for each vehicle. These are referred to as "airborne noise" measurements. In the second test, predominantly structure-borne noise was induced by running the vehicle at a steady speed on a rough roller, giving 224 sets of results for each vehicle. The subsequent statistical analysis was conducted according to body type, tyre type, etc.

In Section 2 the test background is described. Section 3 then describes the results for acoustically induced interior noise. Various results are presented, with many further results being given in Ref. [7]. A rank test is introduced in order to investigate whether there are any particular vehicles which are extreme in either having very good or poor acoustic performance. The $\chi^2$ statistical test is applied to the statistical distribution of the normalised response data. Similar results are presented for the rough roller test in Section 4. Concluding remarks are then made concerning the statistics and the likely statistical distributions from which the measured responses are drawn.

It should be emphasised here that the statistical analysis was performed on the linear data, i.e. not on the data expressed in dB, although sometimes the results are presented in dB.

## 2. Test background

### 2.1. Vehicle sample description

Measurements were taken on two sets of cars, referred to as sets A and B, as summarised in Table 1. Set A is a small hatchback model with both a three-door (subset A3, 411 vehicles) and five-door (A5, 403 vehicles) derivative; the total number of vehicles tested in this set is 814. Set B is a mid-sized family five-door car; the number of vehicles in this set is 316. Measurements were thus taken on a total of 1130 vehicles. Both sets included vehicles of various specifications (at least five vehicle level specifications within each set) including diesel and petrol engines, manual and automatic gearboxes, different interior trim levels and different types of wheels and tyres. The latter would vary within each set according to the vehicle level and while there was no further reduction of the data to analyse just a particular identical vehicle subset with identical tyre, wheel and specification (including engine), the comparison of the groups determined by wheel type and identical tyre has been made for the roller-induced noise comparisons, as this is a clearly significant factor leading to different statistical distribution properties to be shown later.

### 2.2. Environmental conditions

Tests were performed in a hemianechoic chamber from November 2002 to 2004, during which period there were various changes to the assembly specification. For each vehicle, a comprehensive record of its specification was recorded and could be used for subsequent subset selections, such as wheel rim type, tyre type and manufacturer, etc. The environmental conditions of the chamber were monitored and the

Table 1
Number of vehicles tested

| Model | Total number tested | Number tested at 19–20 °C | |
|---|---|---|---|
| | | Petrol | Diesel |
| A3 | 411 | 120 | 36 |
| A5 | 403 | 67 | 14 |
| B | 316 | 19 | 74 |

temperature and humidity recorded. Each vehicle was given some time to acclimatise to the ambient chamber conditions. This was at least 30 min, although longer when the outside temperature was much different than the chamber temperature, during which time the setting up of the microphones inside the vehicle took place. If the test work was being conducted in winter, the vehicles were given an additional 20 min in the chamber to warm up with the vehicle doors and tailgate open. Prior to the roller-induced noise tests, the vehicles were run on the rough roller surface to excite the suspension system and bring it up to an operating temperature. The general impression is that the structural transmission is strongly influenced by the temperature-dependent stiffness properties of any rubber suspension components, typically with static stiffness higher at lower temperatures and unrepresentative of the general ride when the system is at operating temperature.

Variations in the environmental conditions and in particular the temperature and (to a lesser extent) the humidity are of concern. Even though the tests were performed in a chamber, the variability in the temperature and humidity were significant. Fig. 1 shows the variation of chamber temperature for the whole data set. The minimum and maximum recorded temperatures were 10 and 29.5 °C; the standard deviation (estimated from the sample) of the temperature variation was 2.26 °C. For comparison, the standard deviation of the temperature variation in the Isuzu vehicles study [6] was 4.5 °C.

There are two main possible effects of the temperature on the measurements. The first is the effect on the speed of sound and the second is the effect on the material properties of structural components and particularly rubber components such as suspension bushes. The speed of sound for the range of temperatures encountered during the testing would vary approximately between 338 m/s (10 °C) and 349.7 m/s (29.5 °C). These levels of variation are perhaps not insignificant and are of a similar order of magnitude, in terms of normalised standard deviation, to levels of variation often seen in measured natural frequencies. The material properties can, however, vary more substantially with temperature.

The vehicles tested at 19–20 °C form a subset of the results from the main population. The sample sizes are shown in Table 1. The effects of temperature can be investigated by comparing the measured responses of this subset with those of the whole population. Generally, it was found in Ref. [7] that the effects of air temperature in the chamber were small for both airborne and rolling road input—examples are given later—and consequently the majority of the results are presented for the whole population.

The minimum and maximum recorded relative humidity was 27% and 91%; the normalised standard deviation of the humidity variation is 0.37. For comparison, the normalised standard deviation of the humidity variation in the Isuzu vehicles study [6] was 0.30–0.33. The speed of sound in air at 20 °C and 27% relative humidity is approximately 343.7 m/s, and at 91% relative humidity 344.5 m/s. The relative humidity can have an effect on the absorption coefficient of the air at high frequencies [10]. For example, at 10 kHz, the absorption coefficient is approximately 0.075 dB/m at 27% humidity, increasing to 0.25 dB/m at 91% humidity. However, this effect is quite small and at the orders of the distances between loudspeaker sources and receivers in the car (<2 m) the difference is much less than 1 dB and is unlikely to have any significant

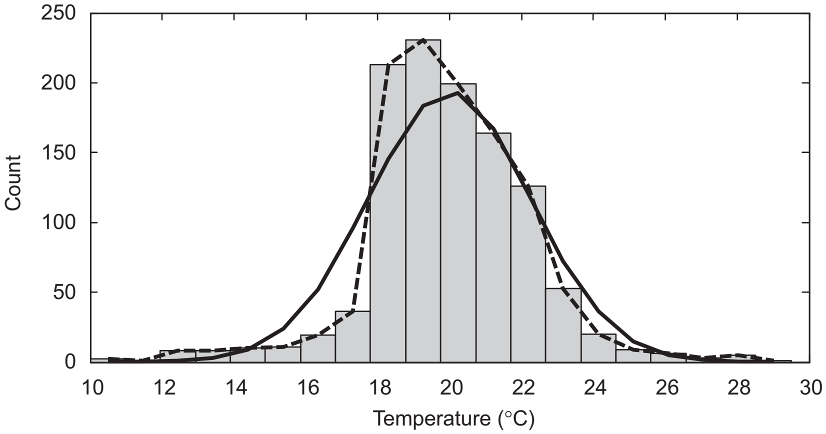

Fig. 1. Chamber temperature distribution (1130 tests): - - - observed data in bins and ___ Gaussian distribution.

effect on the results compared with the other sources of variability in the measurements. In practice, acoustic levels in the car interior are governed by the transmission losses and the absorption of the interior trims.

## 3. Acoustically induced interior noise

### 3.1. Measurement set-up

Six sets of external loudspeaker sources (each loudspeaker a dual cone general purpose studio monitor-type loudspeaker) were used in conjunction with four microphones inside the cabin to estimate the general attenuation of acoustically induced airborne noise of the vehicles. The speakers were connected to a noise generator producing spectrally shaped random noise. The speaker locations were selected to focus specifically on areas near high-level noise sources on the vehicle. One loudspeaker was placed by each of the front and rear tyres for estimating the attenuation due to airborne road noise, with a pair as a set used together when investigating either the front or rear acoustic transparency. A single speaker was placed underneath the engine to examine the transparency of the body to engine noise. A fourth set was a speaker located near the rear floor pan to examine transmission loss for the exhaust noise source. Two further sets, comprising a pair of speakers in each set, were located near the front and rear of the vehicle, to examine the general airborne noise acoustic transparency. To ensure repeatability, the receiver microphones were attached to a frame, which was then mounted inside the vehicle. The microphone locations corresponded to the four occupant outer ear locations. Each exterior speaker arrangement (set) was activated separately and the interior levels at each microphone recorded, as was the level within the chamber that was used as the reference level for the noise reduction (NR) calculation. All the results were stored as 1/3-octave spectra over a frequency range from 50 Hz to 10 kHz.

### 3.2. Results and analysis

#### 3.2.1. 1/3-Octave NR

A typical example of measured airborne noise variability is shown in Fig. 2. This example is for the set A3 and the particular combination of the general front loudspeaker exterior speaker set and the rear right-hand side (looking at the front of the vehicle) internal microphone. Further examples can be found in Ref. [7].

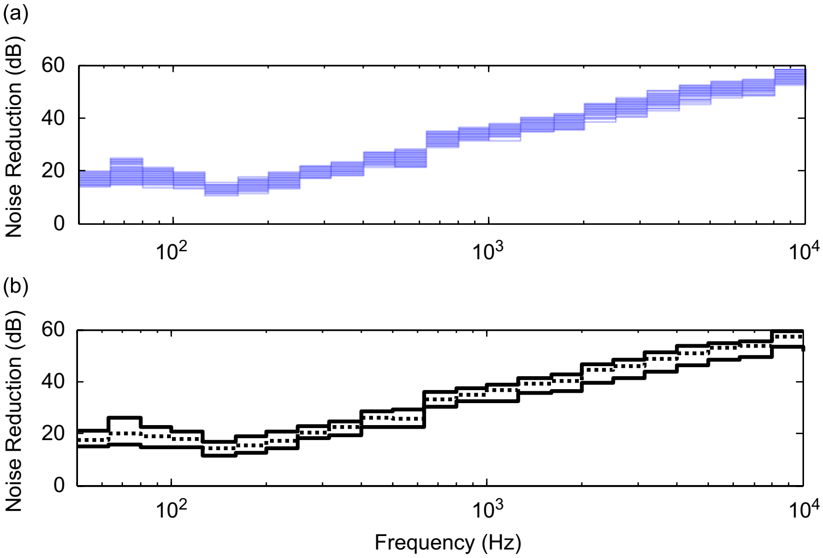

Fig. 2. Typical airborne noise reduction for data set A3 (411 vehicles) at one interior microphone position for one exterior speaker set in third octaves: (a) individual vehicles; (b) ___ maximum and minimum values and … mean values.

Results are shown on a decibel scale and displayed as NR values which are defined as

$$\text{NR [dB]} = \text{excitation level [dB]} - \text{response level [dB]} \tag{1}$$

The excitation level was measured outside of the vehicle by a single microphone not in the direct field of the sound sources and kept in the same position for all tests performed. The acoustic field in the test chamber is not diffuse, but no comparison of the data has been performed for different sound source locations, instead the analysis has considered variability when only the vehicles have been changed. Also shown are the maximum, minimum and average values in each 1/3-octave band. Each average is the average of the NR values (linear values, not the average of the dB values) in the 1/3-octave, subsequently plotted in dB, and not the average of the individual dB values. The 1/3-octave NR levels show a spread, which is typically similar for all body styles and typically spans some 5 dB or so.

It is of interest to discover whether the outlying results, the maximum and minimum in each 1/3-octave band, are in general from particularly good or poor vehicles. If so, these vehicles may be exceptional cases. To investigate this, the vehicles are "ranked" in order of NR level in each 1/3-octave band. Each vehicle is awarded a rank value in each 1/3-octave frequency band, 1 being the lowest and $N$ being the highest, where $N$ is the number of vehicles in that test set. These rank numbers are then averaged over all frequency bands for each vehicle, resulting in a mean ranking for that vehicle which represents its average NR ranking within the population. The distribution of these average rank values can then be examined for outlying results, i.e. vehicles which are consistently worse or better than average. An example distribution is shown in Fig. 3.

As the vehicles were ranked in each 1/3-octave from 1 to $N$, then the mean of the average rank values is $(1+N)/2$. The lowest possible average rank value is 1, and would represent a vehicle, which has the lowest NR in every 1/3-octave band. Similarly, the highest possible rank value is $N$ and would represent a vehicle which has the highest NR in every 1/3-octave band. The distribution of rank values for this vehicle set are well inside the possible limits of 1 and $N$, with a standard deviation which is comparable to that ($\sqrt{N}$) which would be expected were the rank values random (e.g. a random walk process). This indicates that there are only a few vehicles at most, which consistently have the lowest or highest NR over the whole spectrum. Similar distributions were examined for the other two body styles: it was consistently observed that there were no significant outliers.

The statistical distribution of the 1/3-octave NR levels is also of interest. For each data set, there are 576 sets of measurements for each combination of the 1/3-octave bands (24 in total), interior microphone (four microphones) and exterior speaker (six speakers). Examples of normalised linear (not dB) NR for the 125 Hz, 1 kHz and 5 kHz 1/3-octave bands for the set A3 are shown in Figs. 4–6, respectively. The distributions are normalised to zero mean and unit standard deviation. Also shown are various common

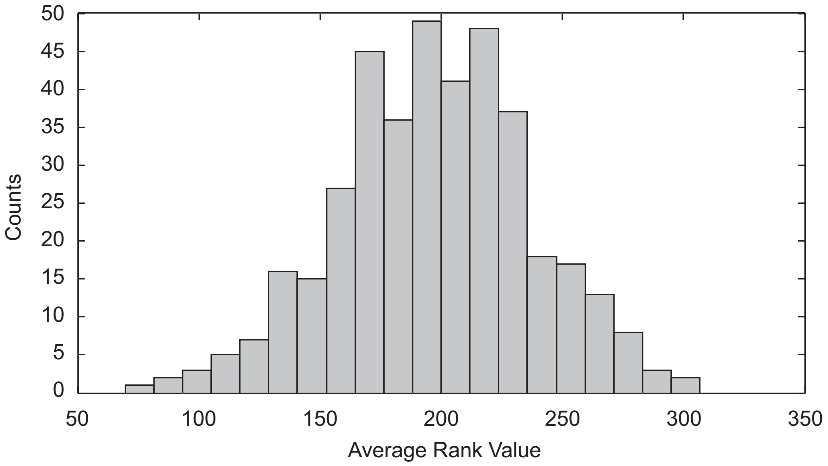

Fig. 3. Distribution of the average rank value for set A3 (411 vehicles) at one interior microphone position for one exterior speaker set.

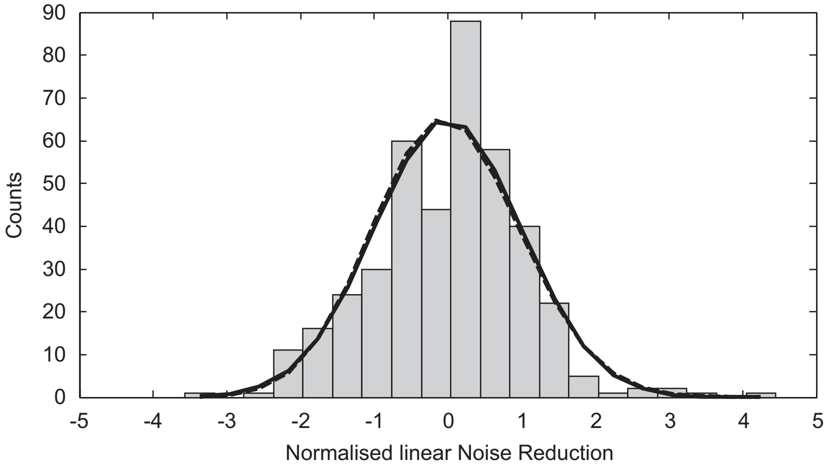

Fig. 4. Distribution of the airborne interior NR for set A3 (411 vehicles) at one interior microphone position for one exterior speaker set in the 125 Hz third octave band: —— Gaussian, - - - lognormal and … gamma distributions.

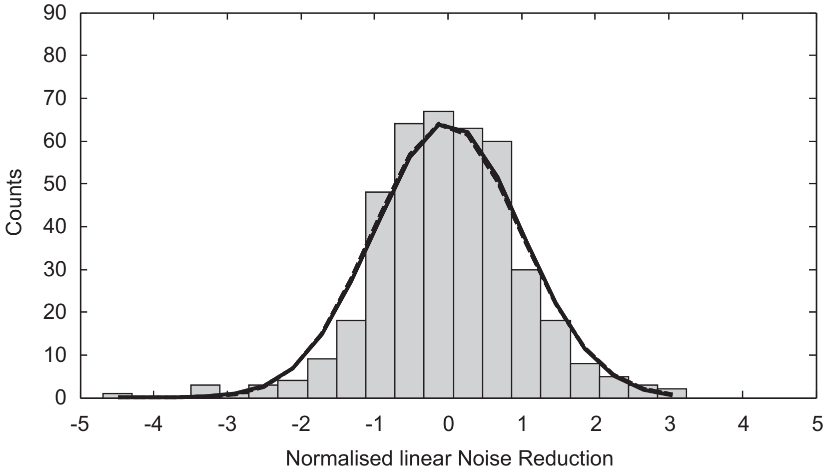

Fig. 5. Distribution of the airborne interior NR for set A3 (411 vehicles) at one interior microphone position for one exterior speaker set in the 1 kHz third octave band: —— Gaussian, - - - lognormal and … gamma distributions.

distributions. The results are very similar for all vehicle variants and show, at least qualitatively, that the distributions are very similar to either lognormal or Gaussian and do not have any particularly unusual characteristics.

The estimated normalised standard deviation ($\sigma/\mu$) for each data set is shown in Fig. 7. The sample standard deviation and mean are used here as estimates of the population standard deviation $\sigma$ and mean $\mu$. There is a slight trend for the normalised standard deviation to decrease with increasing frequency. The values are typically 0.10–0.13. This perhaps large variation is not unexpected as the data sets A3, A5 and B contain a range of different vehicle model specifications including trim levels. These are perhaps inevitable in the manufacturing process over a long period of time. However, the normalised standard deviations are generally significantly lower than those observed for the airborne transfer functions of the Isuzu vehicles [6], where the levels generally ranged between 0.20 and 0.60. This is partly due to the more controlled test facilities in the current study, and in particular a reduction in environmental variability, particularly temperature.

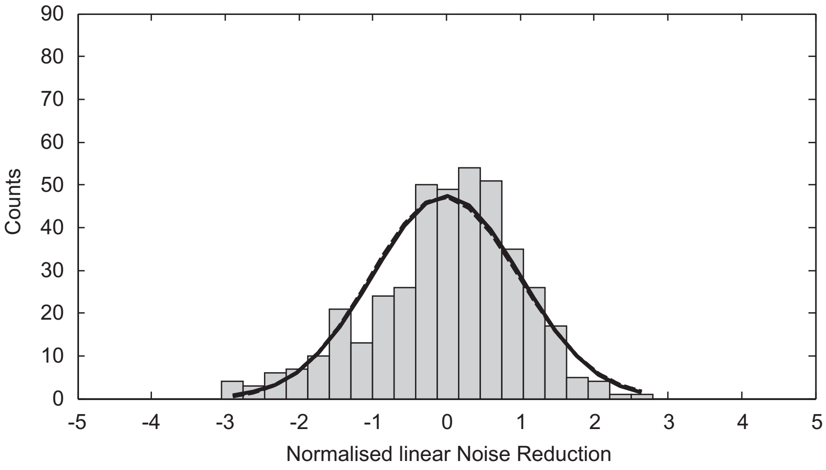

Fig. 6. Distribution of the airborne interior NR for set A3 (411 vehicles) at one interior microphone position for one exterior speaker set in the 5 kHz third octave band: ___ Gaussian, --- lognormal and … gamma distributions.

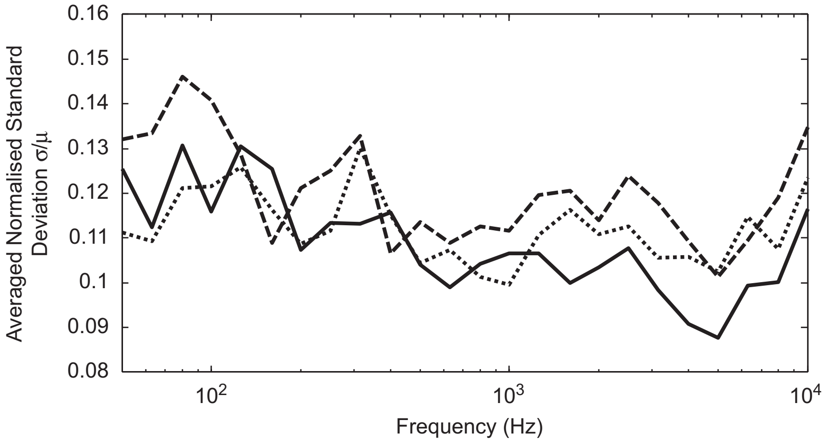

Fig. 7. Averaged normalised standard deviation of the airborne interior NR values: ___ set B, --- set A3 and … set A5.

A $\chi^2$ test was used to determine the goodness-of-fit of several standard distributions to each data set [11]. These can be performed in various ways, for example by considering the values in a particular 1/3-octave band, by taking a subset of the overall NR in a "low-frequency" (50–1000 Hz) or "high-frequency" (>1000 Hz) range or by using the overall NR values for the whole measured frequency range (50–10 kHz). The standard distributions chosen included Gaussian, lognormal and gamma distributions [11]. There is some evidence from previous studies, and some justification from the central limit theorem, that the distribution of the responses of nominally identical structures might be Gaussian, lognormal or close to these distributions. All three chosen distributions become close to Gaussian for certain values of the parameters of the distribution, particularly when the normalised standard deviation is small. The maximum likelihood method was used to estimate the parameters for each of the distributions.

Each set of measurements was divided into 20 bins of equal width, the width depending on the range of the distribution. In order to avoid any outlying results disproportionately affecting the results, the outlying bins were summed to ensure a minimum of four counts in each bin. The $\chi^2$ test is a negative hypothesis test. The results are presented as the percentage of frequency bands for which the $\chi^2$ probability is below 95%, which equates to a 95% confidence that the set of measurements cannot be rejected as having come from the given distribution. The results are shown in Table 2. The distribution that fits the most frequency bands for

Table 2
Results of $\chi^2$ tests of the statistical distribution of the 1/3-octave airborne interior NR values for low frequencies (<1 kHz), high frequencies (>1 kHz) and the whole bandwidth (50 Hz to 10 kHz)

| Data set | Frequency range | Gaussian (%) | Lognormal (%) | Gamma (%) |
|---|---|---|---|---|
| A3 | 50–1000 Hz | 52.7 | 67.0 | 66.1 |
| A5 | | 56.3 | 74.7 | 72.3 |
| B | | 59.2 | 74.7 | 72.9 |
| A3 | 1–10 kHz | 58.3 | 42.1 | 47.1 |
| A5 | | 68.8 | 54.6 | 61.3 |
| B | | 85.8 | 87.1 | 88.3 |
| A3 | 50 Hz to 10 kHz | 55.0 | 56.6 | 58.2 |
| A5 | | 61.5 | 66.3 | 67.7 |
| B | | 70.3 | 79.9 | 79.3 |

The percentages of frequency bands for which $\chi^2 \leqslant 0.95$ are given.

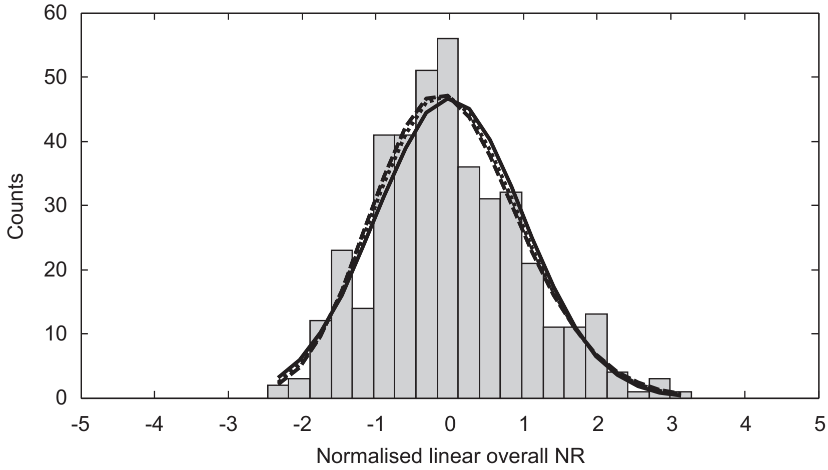

Fig. 8. Distribution of the overall airborne interior NR for set A3 (411 vehicles) over the frequency range from 200 Hz to 10 kHz at one interior microphone position for one exterior speaker set: ___ Gaussian, - - - lognormal and … gamma distributions.

each vehicle model is highlighted. Those distributions that are close to the best fit, say within 5% of the "best fit" value, might also be considered to be good fits to the results.

At lower frequencies (<1000 Hz), the distribution of the levels can be seen to be a good fit to a lognormal distribution. Between 67.0% and 74.7% of the frequency bands cannot be rejected as having come from a lognormal distribution. At higher frequencies (>1000 Hz), a Gaussian distribution is the best fit to the results from sets A3 and A5 (58.3% and 68.8%), but for set B, a gamma distribution fits slightly more of the frequency bands (88.3%), although both Gaussian and lognormal distributions also fit a large percentage of the measured results (85.8% and 87.1%).

A gamma distribution gives the best fit over the whole bandwidth for both the A3 and A5 sets, while a lognormal distribution gives the best fit for set B. However, the differences are small, and generally both lognormal and gamma distributions fit well, with Gaussian distributions giving only slightly less good fit.

### 3.2.2. *Overall NR*

The distribution of the overall cabin NR was also examined. The overall levels are calculated over the frequency range from 200 Hz to 10 kHz. The very low-frequency bands were excluded because they dominate the overall level and tend to be more affected by background noise issues (due to low excitation levels from the

Table 3
Results of $\chi^2$ tests of the overall airborne interior NR (200 Hz to 10 kHz)

| Data set | Gaussian (%) | Lognormal (%) | Gamma (%) |
|---|---|---|---|
| A3 | 54.2 | 37.5 | 37.5 |
| A5 | 66.7 | 66.7 | 66.7 |
| B | 58.3 | 62.5 | 62.5 |

The percentages of frequency bands for which $\chi^2 \leqslant 0.95$ are given.

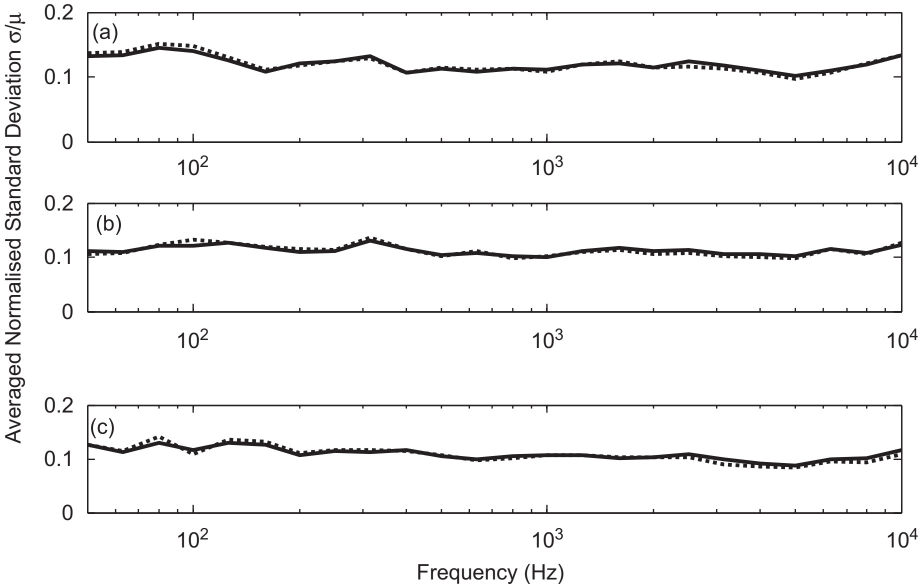

Fig. 9. Averaged normalised standard deviation of the airborne noise reduction for __ the ensemble and … tests conducted at 19–20 °C: (a) set A3; (b) set A5; and (c) set B.

speakers at these frequencies). The overall NR level is given by

$$\text{overall NR [dB]} = -10 \log\left(\frac{\sum_{j=1,n} 10^{-\mathrm{NR}_j/10}}{n}\right) \tag{2}$$

where $n = 18$ is the number of 1/3-octave bands in the range from 200 Hz to 10 kHz frequency range and $\mathrm{NR}_j$ is the NR level in decibels for the $j$th 1/3-octave band. An example of the distribution of the overall linear NR is shown in Fig. 8 for the set A3. Table 3 shows the results of $\chi^2$ tests for various statistical distributions. A Gaussian distribution is a good fit to the results from each of the vehicle body styles, fitting 54–67% of the results. Lognormal and gamma distributions are also a good fit to the results for sets A5 and B, and slightly better than Gaussian for the latter; however, these distributions approach Gaussian as $\sigma/\mu \to 0$.

The effects of the test temperature were also investigated by comparing the ensemble statistics with those for tests conducted only at 19–20 °C. Generally there was little difference. For example, Fig. 9 shows the average normalised standard deviations for the NR for airborne noise. The conclusion is that manufacturing variability is larger than variability due to the test temperature for the tests conducted here.

### 3.3. Airborne noise summary

Again, the statistics were determined from the linear levels, although results are often quoted, and NR levels plotted, in dB. The 1/3-octave NR levels typically have a spread of 5 dB or so. No evidence was found to suggest that there were outlying vehicles, i.e. vehicles with consistently low or high NR levels across the whole spectrum. The normalised standard deviation was typically 0.1 or higher, with there being a slight trend for it to decrease with increasing frequency, perhaps because the bandwidth of each 1/3-octave band increases with frequency, and also because the modal density and modal overlap generally increase with frequency.

At lower frequencies, a lognormal distribution was a somewhat better fit to the 1/3-octave NR levels than a Gaussian distribution, while the reverse is true at higher frequencies. Overall, both Gaussian and lognormal distributions gave reasonable fits.

One hypothesis for the differences between the statistical distributions of the 1/3-octave NR levels at low and high frequencies is that it may be due to sealing of the vehicles. At lower frequencies, the NR level may be controlled by the transmission loss of the vehicle body, whereas at higher frequencies it is more likely to be affected by leakage and sealing of small holes in the body. If this is the case, the different mechanisms may have different distributions.

Examination of the distribution of the overall NR levels suggests a Gaussian distribution to be the most fairly representative, except for set B, for which a lognormal distribution was a somewhat better fit.

## 4. Roller-induced interior noise

### 4.1. Measurement set-up

For these roller-induced road noise measurements, the vehicle was installed on a dynamometer roller test rig. The roller had a rough surface consisting of a random pattern of projections to simulate a coarse impact input into the tyre. The tests were conducted on the rough surface at a steady speed of 50 km/h with 1/3-octave interior noise measurements taken from 20 Hz to 10 kHz using the same microphone test frame used for the

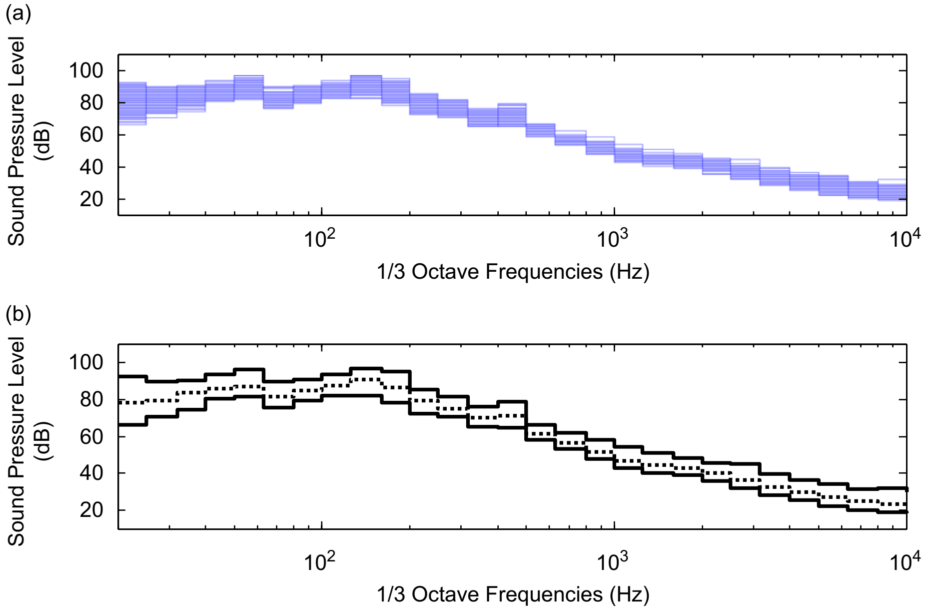

Fig. 10. Typical roller-induced noise (dB ref $20 \times 10^{-6}$ Pa) for data set A3 (407 vehicles) at one interior microphone position for rough roller surface on the front axle in third octaves: (a) individual vehicles; (b) ___ maximum and minimum values and … mean values.

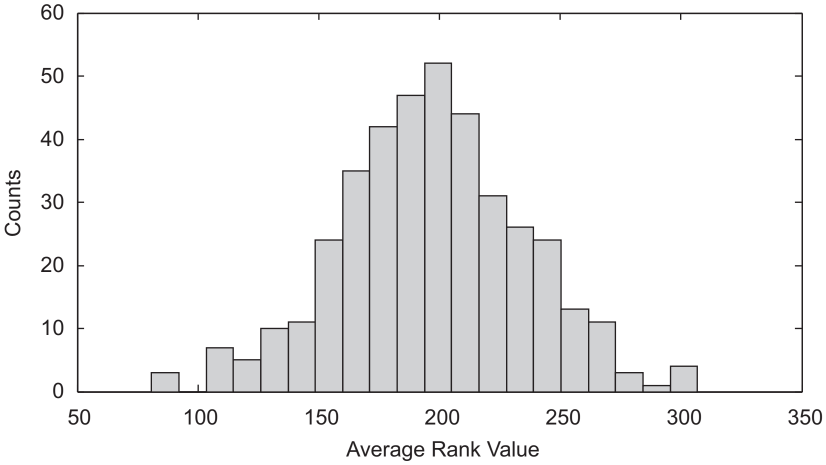

Fig. 11. Distribution of the average rank value for set A5 (403 vehicles) at one interior microphone position for rough roller surface on the front axle.

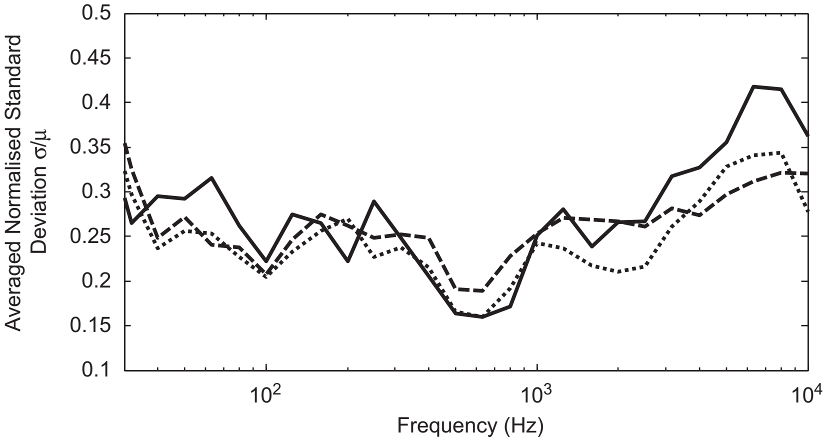

Fig. 12. Normalised standard deviation of the roller-induced noise: —— set B, - - - set A3 and … set A5.

airborne-induced noise measurements. Each axle of the vehicle was excited separately, thus with four interior microphones and 28 1/3-octave frequency bands, there are 224 sets of results for each of the vehicle tests. The results were analysed in groups according to body type, etc.

### *4.2. Results and analysis*

#### *4.2.1. 1/3-Octave analysis*

A typical example of the variability of road-generated noise is shown in Fig. 10 for the data set A3. Also shown are the maximum, minimum and average levels in each 1/3-octave band. The roller-induced noise shows variability of 10–30 dB or so, somewhat more than the airborne NR (Fig. 2).

Using a similar method to that described in Section 3, the results were ranked to check for extreme outlying vehicles. In each 1/3 octave, the vehicles were ranked from 1 to $N$ and so the mean value of the average rank values is $(1+N)/2$. A typical distribution of the average rank values is shown in Fig. 11. It can be seen, for this example, that there is a group of three vehicles at the lower end of the average rank values, which are generally quieter than the rest of the population and a group of four vehicles for which the levels are generally higher than the rest of the population. However, neither group is close to the extreme outer limits for the average

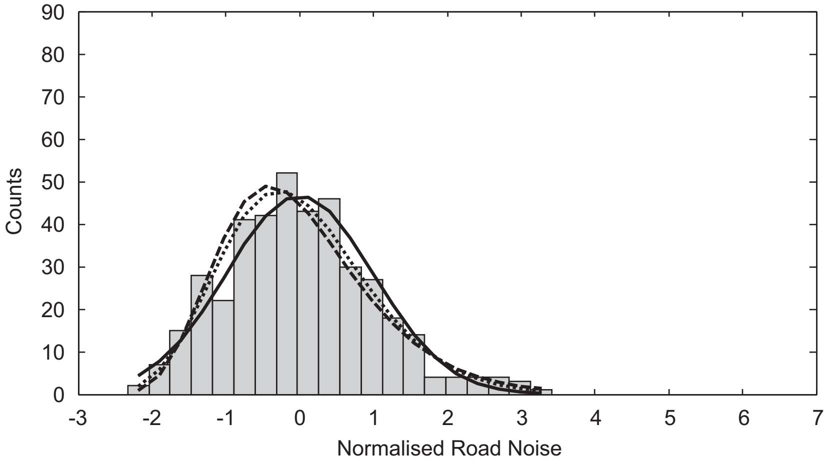

Fig. 13. Distribution of the roller-induced noise for set A3 (411 vehicles) at one interior microphone position for the rough roller on the front axle in the 125 Hz third octave band: —— Gaussian, - - - lognormal and … gamma distributions.

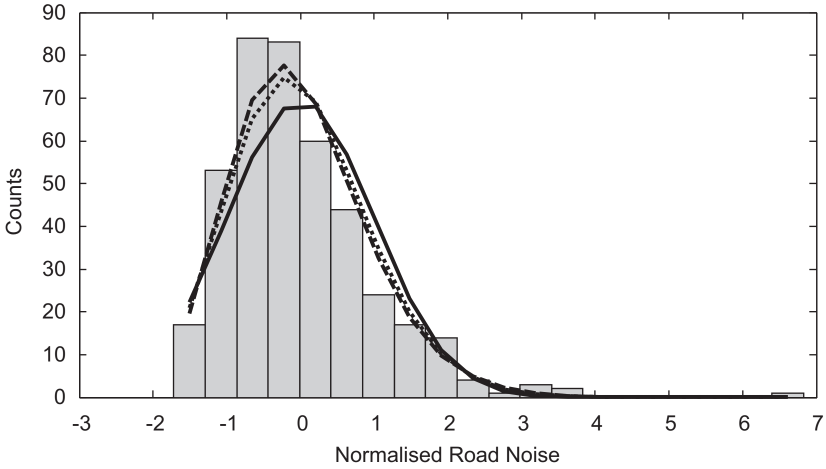

Fig. 14. Distribution of the roller-induced noise for set A3 (411 vehicles) at one interior microphone position for the rough roller on the front axle in the 1 kHz third octave band: —— Gaussian, - - - lognormal and … gamma distributions.

rank values (1 and $N = 403$ in this case). Hence, there are not any significant outlying members of the population. Similar distributions were observed for the sets A3 and B.

The normalised standard deviation for each data set is shown in Fig. 12, which shows the average of the eight roller-induced noise data sets (four internal microphones, front and rear axle) for each model body type. For each combination (roller at either front or rear wheels and internal microphone), the value $\sigma/\mu$ of the linear values of the NR in the band is evaluated and then the average of these eight quantities are calculated and plotted. The level of variability within the road noise data is quite high with the averaged normalised standard deviation ranging from about 0.16 to 0.42. One reason for this is that the vehicles were fitted with a range of different tyres and the tread pattern and size is likely to have a significant effect on the roller-induced noise, hence increasing the standard deviation of each data set. The normalised standard deviation below 1 kHz can be seen to be generally lower than that above 1 kHz, which might be due to high-frequency contributions such as squeaks and rattles or greater sensitivity to tyre tread pattern and size. Generally, the standard deviation for data sets of vehicles with the same rim material and tyre type is smaller, being typically 0.2.

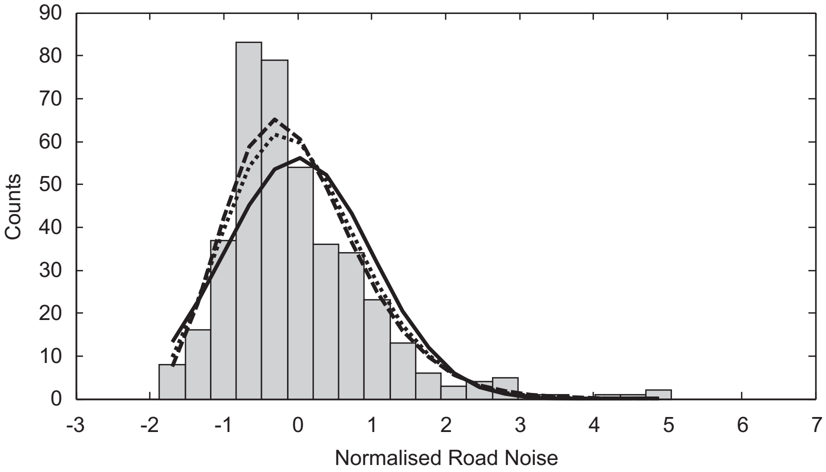

Fig. 15. Distribution of the roller-induced noise for set A3 (411 vehicles) at one interior microphone position for the rough roller on the front axle in the 5 kHz third octave band: ___ Gaussian, - - - lognormal and … gamma distributions.

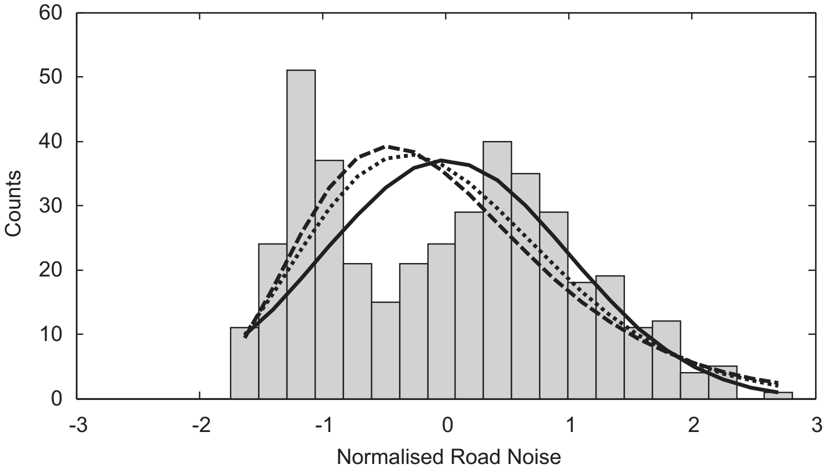

Fig. 16. Distribution of the roller-induced noise for set A3 (411 vehicles) at one interior microphone position for the rough roller on the front axle in the 315 Hz third octave band: ___ Gaussian, - - - lognormal and … gamma distributions.

The subsequent statistical analysis was again conducted on the linear data. Examples of the typical distributions of the noise levels, normalised to have zero mean and unit standard deviation, in 1/3-octave band levels at low, mid and high frequencies are shown in Figs. 13–15, respectively. The examples shown are typical of the results for most frequency bands for all the data sets. However, the results for one particular frequency band, at 315 Hz, are different. This frequency band would normally contain the tyre cavity resonance frequency and the response might be expected to depend more sensitively on rim and tyre construction. The distribution for data set A3, Fig. 16, is distinctly bi-modal. This arises because different tyre sizes and wheel rim materials were used, subsequently plotted as two distinct sets to show the effect in Figs. 18 and 19. Data set B does not display such a bi-modal distribution in this frequency band (Fig. 17). The distributions for vehicles with nominally identical tyres and rims do not show bi-modal behaviour. For example, Figs. 18 and 19 show the distributions for vehicles of type A3 with steel and aluminium alloy rims and a single tyre size (175/65-R14) from the same manufacturer.

As before a $\chi^2$ test was applied to evaluate the goodness-of-fit of several distributions for the full data sets and the subsets with the same wheel and tyre types for models A and B. The percentages of the data sets that

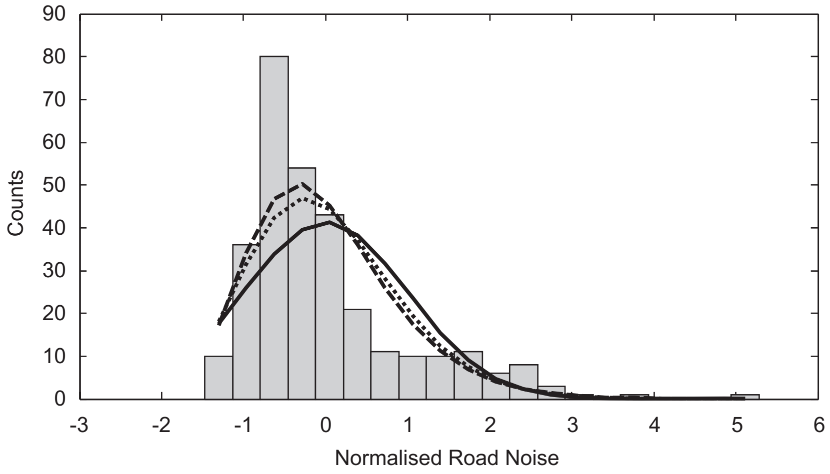

Fig. 17. Distribution of the roller-induced noise for set B (316 vehicles) at one interior microphone position for the rough roller on the front axle in the 315 Hz third octave band: ___ Gaussian, - - - lognormal and … gamma distributions.

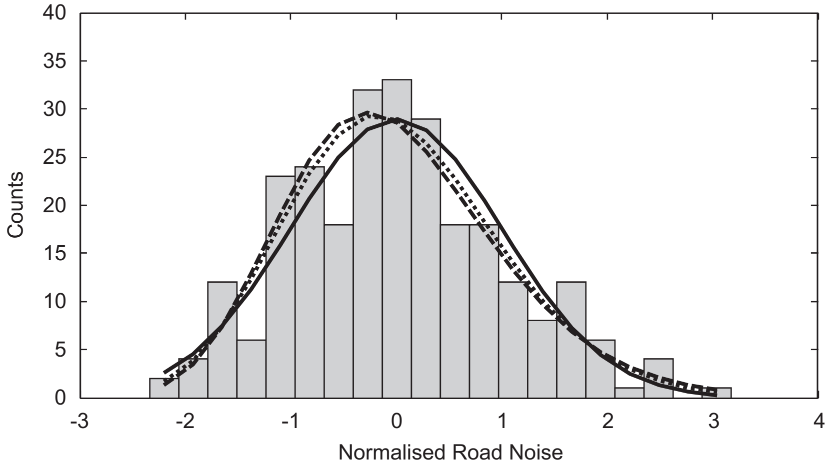

Fig. 18. Distribution of the roller-induced noise for set A3 with steel rims (263 vehicles) at one interior microphone position for the rough roller on the front axle in the 315 Hz third octave band: ___ Gaussian, - - - lognormal and … gamma distributions.

cannot be rejected as having come from each distribution are shown in Table 4. A lognormal distribution was found to be the best fit to the results from all the data sets with between 40.6% and 46.4% of the frequency bands having $\chi^2 \leqslant 0.95$. When further restricting the data for set A to those vehicles having nominally identical wheels and tyres then significantly more of the frequency lines, 62.9%, were found to be a good fit to a lognormal distribution.

At higher frequencies, above 1 kHz, the interior noise measurements could be affected by squeaks and rattles. Such intermittent noises inside the cabin are highly variable and unrepeatable. In order to understand the underlying distribution of the measured noise without the additional variability of squeaks and rattles, the results for vehicles with nominally identical wheels and tyres were analysed for a limited frequency range from 20 Hz to 1 kHz. The results are given in the last row of Table 4. It can be seen that the number of frequency lines that are a good fit to a lognormal distribution increases significantly from 40.6% to 77.8%. The effect of limiting the frequency range (to exclude squeaks and rattles) thus has the effect of increasing the number of frequency bands that are a good fit to a lognormal distribution from 62.9% to 77.8%.

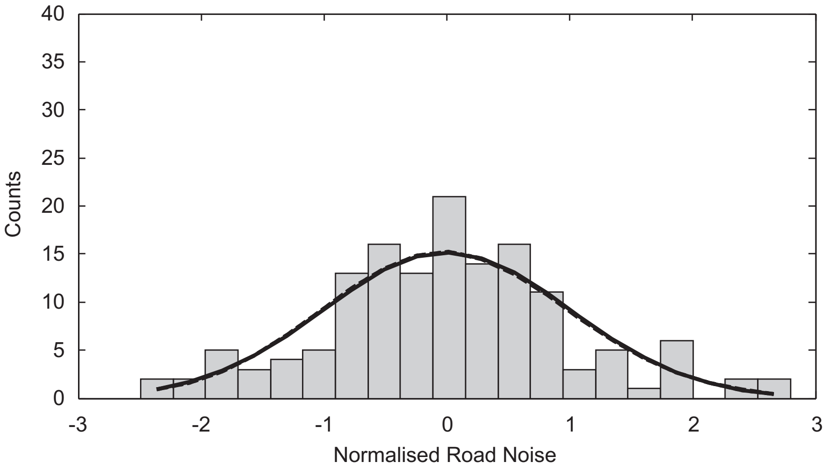

Fig. 19. Distribution of the roller-induced noise for set A3 with aluminium rims (144 vehicles) at one interior microphone position for the rough roller on the front axle in the 315 Hz third octave band: ___ Gaussian, - - - lognormal and … gamma distributions.

Table 4
Results of $\chi^2$ tests of the statistical distribution of the 1/3-octave roller-induced noise

| Data set | Gaussian (%) | Lognormal (%) | Gamma (%) |
|---|---|---|---|
| A3, all rims/tyres | 9.8 | 40.6 | 27.7 |
| A5, all rims/tyres | 12.1 | 43.3 | 34.4 |
| B, all rims/tyres | 17.4 | 46.4 | 41.5 |
| A3, steel rims (175/65-R14), common tyre manufacturer, all 1/3 octave bands | 35.7 | 62.9 | 55.4 |
| A3, steel rims (175/65-R14), common tyre manufacturer, 20 Hz to 1 kHz 1/3-octave bands | 50.0 | 77.8 | 71.5 |

The percentages of frequency bands for which $\chi^2 \leqslant 0.95$ are given for the full data sets with all wheel sizes and tyres and for the restricted set with steel rims (175/65-R14) and a common tyre manufacturer.

Table 5
Results of $\chi^2$ tests of the statistical distribution of the overall roller-induced noise (50 Hz to 1 kHz)

| Data set | Gaussian (%) | Lognormal (%) | Gamma (%) |
|---|---|---|---|
| A3 | 87.5 | 87.5 | 87.5 |
| A5 | 37.5 | 62.5 | 62.5 |
| B | 12.5 | 25.0 | 25.0 |

The percentages of frequency bands for which $\chi^2 \leqslant 0.95$ are given.

### 4.2.2. *Overall noise levels*

The distribution of the overall roller-induced noise level was also examined. Table 5 shows the results of $\chi^2$ tests with the overall level being calculated as that from 50 Hz to 1 kHz. Data set A3 is a good fit to a Gaussian, lognormal or gamma distribution, data set A5 is a good fit to a lognormal or gamma distributions, while the results from set B, shown in Fig. 20, do not fit any of these distributions well.

Fig. 21 shows the average normalised standard deviations for the overall roller-induced noise levels together with those for vehicles tested only at 19–20 °C. Again, the effects of temperature are small, indicating that manufacturing variability is larger than that due to temperature for the tests conducted.

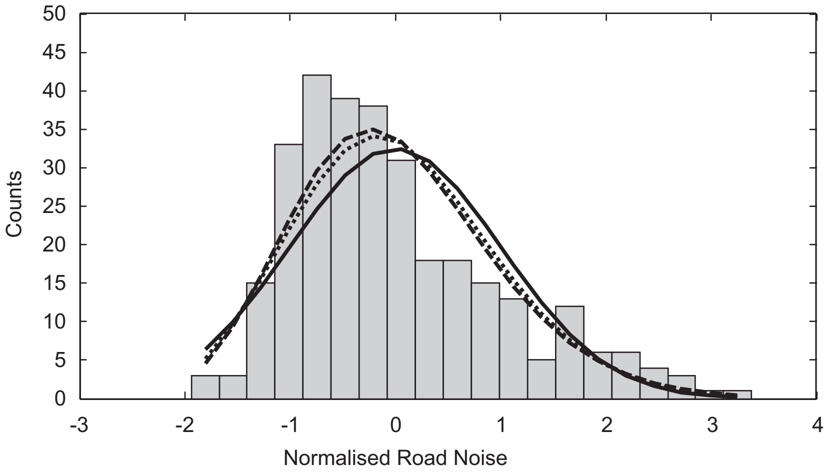

Fig. 20. Distribution of the overall roller-induced noise for set B (316 vehicles) at one interior microphone position for the rough roller on the front axle: ___ Gaussian, - - - lognormal and … gamma distributions.

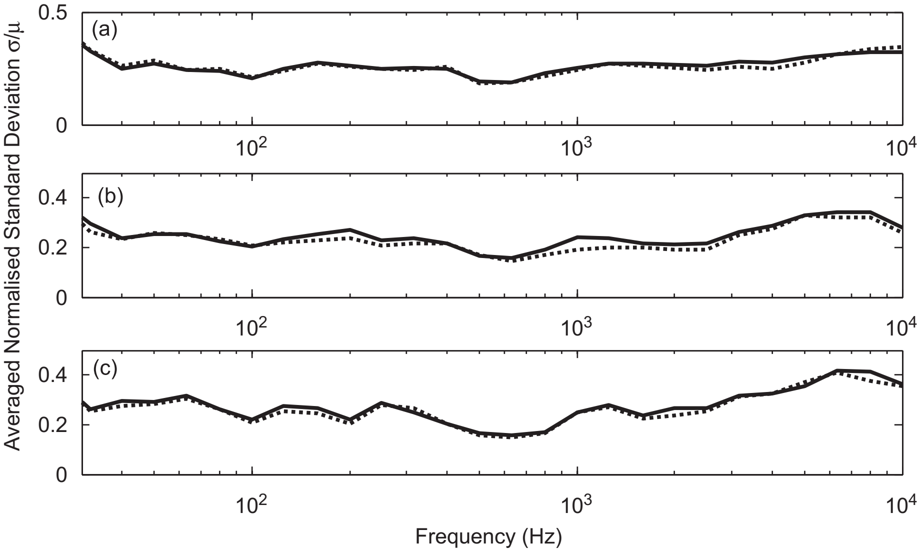

Fig. 21. Averaged normalised standard deviation of the roller-induced noise for ___ the ensemble and … tests conducted at 19–20 °C: (a) set A3; (b) set A5 and (c) set B.

### 4.3. Roller-induced noise summary

The main frequency range of interest for road noise is 20–1500 Hz or so. There was generally considerable variability in the roller-induced noise, with individual 1/3-octave levels varying by typically 15 dB or so and with the normalised standard deviation being in the range 0.2–0.35 or so. There is no reason to suggest that there were any vehicles, which were consistently noisier or more quiet across the whole spectrum. One main reason for the large variability is that different wheel rim and tyre constructions were used, with data set A3 exhibiting a clear bi-modal distribution in the 315 Hz 1/3-octave band. The rim and tyre types affect not only the excitation but also the response. Variability above 1 kHz or so is also thought to be partly due to squeaks and rattles. The normalised standard deviation for vehicles with the same rim and tyre type was lower in the frequency range 40–600 Hz, and was typically 0.2 or so.

The distribution of the linear roller-induced noise level in each 1/3-octave frequency band was well described by a lognormal distribution. The overall level of road noise can be well described by either a lognormal or a gamma distribution.

## 5. Concluding remarks

In this paper, the results of a statistical analysis of an extensive series of measurements of the acoustic response of vehicles were presented. The measurements were taken for two types of test: acoustically induced airborne cabin noise and roller-induced road noise excitation. The air temperature and humidity within the test chamber were recorded, the former ranging from 10 to 29.5 °C, with a standard deviation of 2.26 °C. The statistical analysis was conducted on the linear data, with some results being presented in dB for convenience. Three vehicle types were tested comprising a small three and five-door hatchback variant (sets A3 and A5, respectively) and a mid-sized five-door family car (set B). As is normal in the production environment, the vehicle specifications vary due to, for example, trim and engine type, wheel rim and tyre type, etc. Results for the mean, standard deviation and distribution of the responses were presented. Further examples can be found in Ref. [7].

For both types of excitation, it was seen that the effects of temperature are small, indicating that manufacturing variability is larger than that due to temperature for the tests conducted. It was also observed that there were no significant outlying vehicles, i.e. there were at most only a few vehicles that consistently have the lowest or highest noise levels over the whole spectrum.

The airborne cabin noise measurements used external speakers as noise sources. The 1/3-octave NR levels typically had a spread of 5 dB or so and the normalised standard deviation was typically 0.1 or higher, there being a slight trend for it to decrease with increasing frequency. Regarding the distribution of the 1/3-octave NR levels, at lower frequencies a lognormal distribution was a somewhat better fit than a Gaussian distribution, while the reverse was true at higher frequencies. Overall, both Gaussian and lognormal distributions gave reasonable fits. For the distribution of the overall NR levels, a Gaussian distribution was the most representative except for set B, for which a lognormal distribution was a somewhat better fit. The differences in distributions may be due to different transmission mechanisms. At higher frequencies the airborne cabin noise is likely to be highly dependent on leakage and sealing of small holes in the body, whereas at lower frequencies the NR level may be controlled by the mass and transmission loss of the vehicle body. In summary, as a simple description of the response variability, it is sufficient for this series of measurements to assume that the linear acoustically induced airborne cabin noise is best described by a Gaussian distribution with a normalised standard deviation between 0.09 and 0.145.

The roller-induced road noise tests were conducted on a test rig with simulated coarse road input. There was generally considerable variability in the roller-induced noise, with individual 1/3-octave levels varying by typically 15 dB or so and with the normalised standard deviation being in the range 0.2–0.35 or more. One reason for the large variability is that different wheel rim and tyre constructions were used and these affect not only the excitation but also the response. For vehicles with nominally identical wheel rims and tyres, the normalised standard deviation for 1/3-octave levels in the frequency range 40–600 Hz was shown to reduce to 0.2 or so. Variability above 1 kHz or so is also thought to be partly due to squeaks and rattles. The distribution of the linear roller-induced noise level in each 1/3-octave frequency band was well described by a lognormal distribution. The overall level of road noise can be well described by either a lognormal or a gamma distribution. In summary, as a simple description of the response variability, it is sufficient for this series of measurements to assume that the roller-induced road noise is best described by a lognormal distribution with a normalised standard deviation of 0.2 or so, but that this can be significantly affected by the tyre and rim type, especially at lower frequencies.

The measurements summarised here comprise an extensive study of the variability of the acoustic response of vehicles due to manufacturing variations and changes in vehicle specification. They contribute to the information available concerning levels of variability typically found. The engineer typically is interested in mean noise levels, their standard deviations and perhaps confidence limits or percentiles. While it is relatively straightforward to estimate the mean and standard deviation from relatively few observations, estimating the statistical distribution or other statistics requires many more observations. Thus, there are certain advantages in being able to make a reasonable assumption concerning the distribution. This paper suggests reasonable assumptions, although the results, of course, might differ for a different type of vehicle. Finally, it was also seen that changes in specification such as trim, minor body modifications and, in particular, tyre and rim type might cause significant variability from one specification to another, and this provides a real challenge to the engineer concerned with the production of robust, low noise products.

## Acknowledgements

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