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TRAFFIC NOISE EMISSION MODELLING AT LOWER SPEEDS

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Exposure to road traffic noise in urban areas is a serious concern for human health. Recently, the focus of noise abatement policies increasingly included secondary (collector) and tertiary (local) streets in densely populated areas where noise exceeds the limits. Reducing noise pollution at its source is the most effective way of noise abatement. Besides the construction of low-noise road surfaces, the reduction of speed limits constitutes an effective measure. Today's estimates for a potential reduction of noise due to speed reductions at lower speeds are often based on calculations with national standard models which are not designed for the low-speed range. The attainable noise reduction depends strongly on several influencing variables which are not implemented in these models. This study elaborates the noise emission of a modern vehicle fleet at lower speeds. It analyses different influencing factors related to engine and tyre characteristics and differentiated between rolling noise and propulsion noise. It reveals significantly lower cross-over speeds between rolling and propulsion noise for passenger cars than existing traffic noise emission models. The results, moreover, highlight the need for taking into account the specific influencing factors as well as future shifts in the vehicle fleet for accurate noise emission modelling at speeds below 50 km/h.

1. Introduction

Exposure to road traffic noise in urban areas is a serious concern for human health. Recently, the focus of noise abatement policies increasingly included secondary (collector) and tertiary (local) streets in densely populated areas where noise exceeds the limits. Reducing noise pollution at its source is the most effective way of noise abatement. An effective measure, besides the application of low-noise road surfaces, is reducing the speed limits. Due to their cost effectiveness and their benefits regarding safety, traffic calming measures to speeds below 50 km/h have become increasingly popular in Europe and elsewhere. Today's estimates for a potential reduction of noise due to speed reductions at lower speeds are often based on calculations with national standard models. These models, however, are often not designed for this speed range. The attainable noise reduction strongly depends on several influencing variables which are not implemented in models focused for speeds of 50 km/h and above.

The study [1] showed good consistency between several traffic noise models (TNMs) used within Europe at speeds above ~40 km/h. However, at lower speeds a rather large range of predicted noise levels was found. The most important variables causing this variation in the different model results are the actual average driving speed (and the related gear selection), the driving behaviour and the vehicle fleet and its tyres. This study discusses these influencing factors and investigates their impact on noise emissions. The main focus in this study is 1) to analyse vehicle rolling noise and propulsion noise emission properties in the low speed range and 2) to explore the impact of vehicle fleet changes on noise emissions by investigating the noise generation at low speeds for different vehicle categories such as petrol- or diesel-driven, hybrid and electro cars.

2. Novel established Traffic Noise model at lower speeds

2.1 Measurement campaign

The measurement campaign took place at the Dynamic Test Centre in Vauffelin, Switzerland on 22 April 2015 and was particularly designed firstly, to illustrate the complex transition between rolling and propulsion noise at lower speeds and secondly, to determine the influence of driving behaviour to the total noise emission. A selection of 22 representative and modern passenger cars of common size and type (see Table 1) delivered rolling noise, total noise and acceleration noise emission levels for 18 instructed pass-by scenarios between 20 and 50 km/h and for the gears 1 to 4.

During the campaign the sky was clear without any precipitation and a minimum and maximum temperature of 13 and 22 °C was observed.

Table 1: Analysed tyres and vehicles during the measurement campaign.

vehicle number	vehicle	engine	cubic capacity [ccm]	date of 1st registration	tyre
1	Ford USA, Mustang 5.0i-V8 GT	petrol	4951	2015	Pirelli Pzero
2	Volkswagen Touran	petrol	1390	12.03.2009	Michelin EnergySaver Xgreen
3	Toyota Highlander	hybrid	3331	30.07.2014	Toyo A20 OpenCountry
4	Audi A1 1.4 TFSI CoD Sb	petrol	1395	07.11.2013	Continental PremiumContact 2
5	Toyota Auris HSD	hybrid	1798	15.04.2014	Dunlop SportFastResponse
6	Volkswagen Touran 2.0D Blue Motion	diesel	1968	06.01.2012	Michelin EnergySaver
7	Subaru Impreza	diesel	1998	05.04.2011	Dunlop SportBlueResponse
8	Volkswagen T5 California TDI	diesel	1968	27.02.2012	Bridgestone Duravis
9	Volkswagen Golf VII 1.4 TSI 5	petrol	1395	11.04.2013	Bridgestone Turanza ER300
10	Volvo XC60 D3 AWD	diesel	2400	15.10.2010	Pirelli Scorpion Zero
11	Citroen C4 Picasso 1.6i	petrol	1598	28.09.2010	Michelin Primacy HP
12	Volkswagen Golf VI 1.4 TFSI	petrol	1390	26.07.2011	Continental WinterContact
13	Renault Espace 2.0 DCI	diesel	1995	18.05.2006	Nokian ZG2
14	BMW i3	electric	647	25.09.2014	Bridgestone EcoPia EP500
15	Skoda Octavia C 1.8 TFSI	petrol	1798	16.12.2011	Dunlop SportMaxx RT
16	Audi A3 SB 2.0 TDI	diesel	1968	22.02.2013	Continental SportContact 5
17	Peugeot308 SW 1.6 HDI FAP	hybrid	1560	04.10.2012	Continental WinterContact TS830
18	VW e-Golf	electric	n/s	29.07.2014	Continental WinterContact TS850
19	Mini Cooper	petrol	1598	14.06.2002	Star Performer Winter A
20	Toyota Previa 2.4	petrol	2362	15.10.2004	Michelin EnergySaver
21	Mercedes-Benz Viano 3.0 CDI	diesel	2987	01.07.2013	Dunlop SportMaxx RT
22	Mercedes-Benz 313 CDI	diesel	2143	05.11.2012	Continental Vanco Winter 2

To separate the rolling and propulsion noise, acoustical Coast-by and Controlled Pass-by [2] measurements were performed at constant speeds. In order to assess both, the driver's character as well as the influence of traffic calming measures of the specific low speed situation (e.g. speed bump, non-priority crossings etc.), real accelerated pass-by events [3] were reproduced by combining one of two different driving styles (prudent or impetuous) with one of two different acceleration behaviours (discontinuous or after stopping).

2.2 Statistical survey of driving behaviour

To incorporate the influence of specific driving behaviour at different speeds, it was necessary to gain a detailed knowledge of the effective driving behaviour in reality, as well as on the effective gear-speed-distribution. Both were acquired in a statistical survey of driving behaviour carried out at five different traffic situations with a speed limit of 30 km/h, together with one reference situation with a speed limit of 50 km/h. All measurement sites were situated in two large Swiss agglomerations and had moderate to high traffic volumes. During the measurement, the speed of every passing car was measured with a Sierzega SR4 radar. The gear of each passing car was estimated acoustically. Additionally, the acceleration type (discontinuous or after stopping) and driving style (prudent or impetuous) were estimated acoustically and categorized (these results are discussed in detail in [4]). In this manner, almost 4'700 cars were measured and rated, and formed a unique dataset of effective driving behaviour.

2.3 Establishing the emission approach

The emission approach in this study is established by combining the emission data acquired from the measurement campaign with the statistical data acquired from the survey of driving behaviour at real low-speed situations. The emission approach considers (a) rolling noise and the influence of the road surface, (b) propulsion noise and (c) acceleration noise. Whilst the rolling noise model is directly derived from the coast-by measurements, the propulsion noise model is based on the fact that rolling noise and propulsion noise add up to the total noise at constant speed and gear. Acceleration events are considered via the total noise emissions from the corresponding acceleration scenario.

For some passenger cars with hybrid engines a declutching of the engine was not possible. For those cars it was not possible to measure valid rolling noise emissions. Under the assumption that driving at low-speeds is powered by the battery, these cars are treated as electric vehicles without any noise emissions of the engine.

A detailed description of the methods including the measurement campaign, the statistical survey and the emission approach is presented in [5].

3. Results and discussions

3.1 Rolling and propulsion noise at low speeds

To determine rolling noise and propulsion noise emission properties in the low speed range, a series of coast-by and controlled pass-by measurements were carried out for a selection of 22 representative and modern passenger cars. In Table 2 the modelled rolling noise levels of all tyres mounted on the 22 investigated passenger cars are listed for the third-octave bands between 31.5 to 5'000 Hz along with their vehicle number (in accordance with Table 1), tyre type, tyre tread pattern, EU tyre rolling noise label (if available) and tyre width.

The rolling noise peak frequency of the particular tyre set of each car is denoted with a black frame. All peak frequencies are either lying at 1'000 or 800 Hz having a range between 48.6 to 56.3 dB(A) measured on a very smooth road surface characterized as 5 dB quieter than the reference surface in CNOSSOS. Looking at the spectra in more detail a bimodal distribution with a secondary peak between 315 and 500 Hz in almost all cases was found. This secondary peak was generally found to be more pronounced for tyres with block patterns, which can be explained by tyre induced vibration occurring in this frequency range (see also [6]). Moreover, tyres with block patterns showed above 250 Hz on average 2.4 to 9.3 dB higher noise levels than tyres with longitudinal patterns.

To investigate tyre properties and their rolling noise levels and peak frequency in more detail, tyre width classes are built and shown in Table 2. The tyre with the lowest maximum noise level (LAmax) for rolling noise of 52.4 dB(A) has a width of 205 mm. The highest LAmax is found to be in the group of *wide tyres* with an LAmax of 61.1 dB(A) and a tyre width of 235 mm. The three classes reveal an average for LAmax of 58 dB(A) for *narrow tyres*, 59 dB(A) for *medium tyre width* and 60 dB(A) for *wide tyres*. Therefore, in general an increase in tyre width is expected to increase the LAmax. The sample shows that neither tyre width nor tyre pattern can alone explain the magnitude of the noise levels since they are also dependent upon hardness of the tyre. Tyre hardness is determined by the rubber compounds used when producing the tyre together with their age and usage [7]. Tyre hardness and its influencing factors were not measured or determined in this study. All these factors (apart from tyre ageing and wear) should be represented by the EU tyre rolling noise label [8]. When averaging the rolling noise measurements for different labels, a distinct and consistent difference could only be found for the label with the largest value of 73 dB(A). The tyres with this label show on average 2 dB larger LAmax than tyres with labels between 67 and 72 dB(A). In some of the above discussed categories outliers were found: e.g. within the class *nar-*

row tyres the tyre of vehicle number 15 results in a rather large LAmax of 59.4 dB(A). A possible reason for this discrepancy may be the difference in summer and winter tyre. The occurrence of maximum temperatures of 22°C (see Section 2.1) for winter tyres is rather unusual and it cannot be excluded that the discrepancy arises due to different behaviour of the rubber (different composition and consistency of winter tyres) in the rather high temperature.

Table 2: Measured rolling noise levels (LAFmax at 7.5m distance) for third-octave bands and its sum (LAmax) in dB(A) at a speed of 30 km/h for all analysed tyres described in Table 1 on a road surface characterized as 5 dB(A) quieter than the reference surface in CNOSSOS. The tyres are listed in ascending order of tyre width and grouped in three classes: narrow types, medium tyre width and wide tyres. Tyre type is indicated as "S" for summer tyre and "W" for winter tyre. The tyre tread pattern is denoted with "L" for longitudinal and "B" for block. The frequency at maximum noise level (peak frequency) per vehicle is indicated with a black frame.

	narrow tyres										medium tyre width					wide tyres							frequency [Hz]
vehicle number [-]	14*	17	19	2	6	7	9	12	15	18*	4	8	11	20	5*	22	21	3*	10	13	16	1	
tyre type [-]	S	W	W	S	S	S	S	W	S	W	S	S	S	S	S	W	S	W	S	S	S	S	
tyre tread pattern [-]	L	B	B	L	L	L	L	B	L	B	L	B	L	L	B	B	L	B	B	L	L	L	
tyre rolling noise label [dB(A)]	69/69	72	-	-	70	68	71	72	67	72	-	72	70	70	69	73	68	-	72	73	72	73	
tyre width [mm]	155/175	195	195	205	205	205	205	205	205	205	215	215	215	215	225	235	245	246	254	255	255	265	
	13.0	15.2	13.1	31.5	16.6	15.3	23.3	9.3	19.9	1.9	22.5	15.3	25.3	12.4	15.8	19.0	18.1	12.0	16.1	23.6	23.2	13.6	31.5
	14.7	16.4	18.6	34.8	16.5	18.0	21.6	10.8	21.2	10.7	21.4	16.5	23.3	19.5	18.8	25.9	18.5	17.0	17.2	16.6	20.8	21.1	40
	22.5	17.9	20.9	32.0	22.1	21.9	23.2	20.5	24.3	24.4	22.5	21.1	23.4	22.2	19.9	28.3	23.4	18.5	25.9	28.6	21.4	23.8	50
	27.9	23.3	21.9	28.1	22.8	24.6	25.3	21.6	25.6	22.7	27.8	28.1	30.7	24.9	25.6	31.5	27.6	23.6	27.5	34.4	25.4	23.0	63
	29.9	32.1	28.9	28.5	27.9	28.7	29.9	27.0	32.1	27.8	30.7	27.7	31.7	29.3	35.5	30.4	30.3	27.3	28.2	33.3	30.3	27.2	80
	31.9	30.0	36.1	33.7	31.4	28.6	32.0	28.3	32.5	31.1	32.3	28.7	31.5	31.5	32.3	32.8	31.4	30.6	30.0	33.7	30.3	31.1	100
	32.1	31.8	31.9	31.0	31.0	28.0	30.3	30.1	30.3	24.2	34.1	31.4	33.6	30.6	35.1	37.2	31.8	31.2	30.6	36.9	33.4	32.3	125
	36.2	37.0	34.3	35.1	33.8	33.5	34.1	35.4	34.3	30.8	37.3	35.5	38.1	33.5	38.4	37.4	35.9	36.0	34.1	43.2	34.1	36.1	160
	40.2	39.1	40.9	40.1	37.6	37.8	37.0	39.5	36.8	36.9	37.5	37.6	38.6	37.1	40.3	44.5	42.5	40.3	40.3	42.8	38.6	42.2	200
	41.4	45.7	48.9	46.4	43.3	43.6	43.5	43.3	41.1	40.7	43.2	39.7	43.0	43.4	45.7	44.1	43.2	40.3	45.0	44.9	44.3	43.6	250
	40.2	50.4	48.4	43.2	44.7	39.8	43.1	42.4	42.9	39.1	44.2	42.2	44.9	44.2	46.9	44.8	43.5	40.5	49.4	45.1	44.6	45.7	315
	43.2	44.5	43.6	42.8	49.2	41.0	42.1	42.1	41.5	38.1	43.0	47.1	42.7	43.3	47.3	44.9	42.0	42.5	43.6	44.9	45.4	45.0	400
	42.1	48.2	47.7	47.1	44.1	49.2	44.6	45.9	45.5	35.2	48.4	49.4	44.8	42.8	49.4	47.8	43.3	43.7	45.3	46.2	45.7	47.2	500
	46.7	47.9	48.9	46.4	45.6	46.4	46.5	46.7	48.1	39.9	46.2	51.5	46.4	47.1	48.0	49.8	46.3	46.5	48.2	47.8	47.6	50.8	630
	49.1	49.9	50.6	48.3	48.1	49.5	49.2	49.9	50.3	48.6	48.2	54.4	47.8	49.9	49.7	54.5	51.5	51.8	52.5	49.7	50.6	55.1	800
	50.5	52.4	53.2	52.3	51.0	52.7	52.2	52.7	55.0	42.1	51.6	50.5	50.6	52.5	53.6	55.3	51.0	53.2	56.3	53.2	53.7	55.0	1000
	46.8	51.4	53.0	48.6	47.3	48.8	49.3	50.7	48.6	39.0	50.5	50.5	48.8	48.3	52.6	51.0	47.3	50.0	50.9	50.8	51.4	49.8	1250
	46.1	50.1	51.5	47.1	45.5	48.0	47.5	49.5	47.7	38.6	47.7	51.0	46.5	48.8	49.2	51.0	48.2	52.2	49.1	49.1	48.1	48.3	1600
	47.4	48.9	49.3	47.6	46.0	49.2	48.5	47.3	49.4	39.2	47.0	47.5	46.6	48.3	50.0	48.1	49.2	51.5	48.8	50.4	47.5	50.9	2000
	44.8	45.9	45.7	43.1	42.3	45.5	45.2	46.2	45.6	37.1	46.2	45.1	45.3	44.3	47.4	45.7	44.1	46.5	44.6	46.9	44.3	45.0	2500
	41.4	43.5	41.6	40.6	40.2	41.6	42.1	43.9	42.9	33.7	41.6	41.1	41.0	41.1	43.7	43.1	42.4	43.7	41.5	45.0	40.3	41.9	3150
	39.1	41.7	40.0	38.1	37.2	39.0	40.3	43.5	39.2	36.1	39.2	38.3	39.3	37.1	40.8	41.0	37.5	41.1	40.2	43.1	38.5	38.8	4000
	33.5	35.0	34.7	33.3	31.7	34.0	34.3	35.7	35.3	28.0	32.6	35.3	33.7	34.3	35.7	36.8	34.3	38.5	36.3	45.7	34.0	35.9	5000
LAmax [dB(A)]	57.2	59.9	60.6	58.2	57.5	58.7	58.2	59.0	59.4	52.4	58.4	60.2	57.5	58.4	60.4	61.1	58.3	59.9	60.8	60.0	59.3	61.0	

*: electric and hybrid vehicles for which was not possible to switch off the engine to solely measure the rolling noise. Thus, the total noise was measured instead (however, the propulsion noise in these cases can most likely be neglected)

In Table 3 the calculated propulsion noise levels at a speed of 30 km/h are denoted while driving in gear 2 and 3. The propulsion noise for all electric vehicles is zero and for all hybrid vehicles it is set to zero (for these vehicle categories the total noise, assumed to be the rolling noise, is depicted in Table 2) except for vehicle number 17. For this hybrid car the propulsion and rolling noise were measured separately.

The propulsion maximum noise levels at peak frequency per vehicle are between 48.8 and 62.8 dB(A) for the 2nd gear and between 44.2 and 54.3 dB(A) for the 3rd gear. Thus, at the same speed (in this case 30 km/h) the propulsion noise is lower when driving at high engine speeds compared to driving at low engine speeds. In most cases, the peak frequencies appeared in the frequency range between 630 and 1’250 Hz for both gears. Differences were found between the vehicles powered by petrol and diesel. The investigated vehicles powered by petrol revealed on average higher peak frequencies between 1'000 and 2'500 Hz compared to a range of 630 and 1'250 Hz. Additionally, the petrol powered cars indicate on average lower propulsion maximum noise levels at its peak frequency compared to the diesel powered cars. Driven in 2nd gear mean LAmax$_{gear=2}$ for propulsion noise values resulted in 62.6 dB(A) for diesel powered cars and 59.2 dB(A) for petrol powered cars, while in 3rd gear mean LAmax$_{gear=3}$ for propulsion noise values of 57.2 and 55.0 dB(A) were found for diesel and petrol powered cars, respectively. Thus, at lower engine speeds diesel powered cars seem to emit more noise than petrol powered cars. At higher engine speeds this difference becomes smaller.

Table 3: Propulsion noise levels calculated from the measurements at a speed of 30 km/h driven in 2nd gear (top) and 3rd gear (bottom). The engine is denoted with "p" for petrol powered engines, "d" for diesel powered engines and "h" for hybrid cars. The frequency at maximum noise level (peak frequency) per vehicle is indicated with a black frame.

vehicle number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	frequency [Hz]
powered by	p	p	h	p	h	d	d	d	p	d	p	p	d	e	p	d	h	e	p	p	d	d	
cubic capacity	4'951	1'390	3'331	1'395	1'798	1'968	1'998	1'968	1'395	2'400	1'598	1'390	1'995	647	1'798	1'968	1'560	k.A.	1'598	2'362	2'987	2'143	
date of first registration	2015	2009	2014	2013	2014	2012	2011	2012	2013	2010	2010	2011	2006	2014	2011	2013	2012	2014	2002	2004	2013	2012	
gear 2	19.0	0.0	0.0	0.0	0.0	21.8	15.5	11.6	0.0	0.0	0.0	13.6	0.0	0.0	13.9	0.0	0.0	0.0	13.5	15.7	7.2	17.0	31.5
	27.6	0.0	0.0	22.5	0.0	29.1	24.3	27.2	26.8	17.4	25.1	19.3	28.1	0.0	20.5	27.9	0.0	0.0	19.6	24.8	2.6	0.0	40
	32.4	31.8	0.0	22.1	0.0	28.4	27.0	29.8	25.6	30.9	24.8	25.8	0.0	0.0	26.8	28.8	0.0	0.0	19.1	23.5	24.5	40.4	50
	34.5	25.0	0.0	27.8	0.0	29.0	33.8	27.9	24.8	37.8	34.8	30.0	45.1	0.0	27.9	28.1	29.7	0.0	25.1	24.7	30.7	32.1	63
	37.1	34.5	0.0	32.2	0.0	34.2	40.8	30.3	27.3	31.3	31.3	28.4	0.0	0.0	32.0	36.3	38.6	0.0	41.6	30.0	27.8	33.3	80
	34.5	38.1	0.0	36.2	0.0	37.6	39.8	38.2	30.6	37.2	31.8	32.5	44.5	0.0	31.2	35.5	0.0	0.0	42.5	35.4	27.3	37.1	100
	39.5	34.9	0.0	37.8	0.0	37.2	39.0	39.1	32.5	31.8	32.4	38.9	45.6	0.0	32.5	36.2	36.9	0.0	32.1	27.7	33.2	43.6	125
	40.9	36.6	0.0	41.6	0.0	40.5	46.8	43.5	34.9	37.7	32.2	38.2	48.2	0.0	36.9	41.6	42.3	0.0	37.0	33.3	35.3	44.1	160
	45.6	39.1	0.0	39.5	0.0	45.7	45.3	47.9	39.2	41.3	41.8	40.3	46.6	0.0	43.8	44.0	47.2	0.0	34.7	36.5	39.5	49.6	200
	45.9	41.6	0.0	45.9	0.0	47.0	43.4	51.1	37.8	45.1	44.1	42.1	49.6	0.0	41.6	43.3	44.0	0.0	0.0	41.4	46.9	53.0	250
	45.4	44.8	0.0	44.9	0.0	48.9	43.0	52.9	42.5	43.5	45.4	42.8	47.7	0.0	41.3	44.7	44.0	0.0	43.7	41.5	42.5	53.7	315
	48.3	46.0	0.0	44.4	0.0	45.5	44.3	55.4	41.9	50.9	47.6	46.4	52.2	0.0	47.4	46.0	46.4	0.0	45.1	46.3	46.7	55.2	400
	48.5	45.2	0.0	44.5	0.0	52.3	35.6	55.3	44.1	51.1	46.0	46.1	53.2	0.0	47.5	47.9	49.2	0.0	45.0	47.5	48.2	57.5	500
	48.5	46.0	0.0	48.7	0.0	52.2	47.4	55.5	44.3	52.2	49.5	47.4	52.3	0.0	47.6	49.0	48.1	0.0	45.7	46.3	51.4	57.8	630
	49.4	46.0	0.0	49.2	0.0	53.6	49.8	52.7	45.9	51.8	52.4	46.2	53.3	0.0	49.4	47.2	49.8	0.0	47.8	45.9	50.5	59.9	800
	49.0	46.8	0.0	50.5	0.0	55.4	50.6	52.6	48.8	48.3	54.2	49.8	53.7	0.0	48.8	49.6	49.5	0.0	50.1	50.3	49.9	58.6	1000
	52.7	46.4	0.0	49.4	0.0	54.1	51.1	53.0	48.2	48.1	53.9	49.8	53.7	0.0	53.4	47.1	48.0	0.0	47.2	48.2	52.1	61.6	1250
	48.9	49.1	0.0	48.2	0.0	52.2	50.3	54.4	45.8	48.9	51.1	50.4	53.5	0.0	52.3	46.6	44.9	0.0	47.9	48.1	50.7	62.8	1600
	50.1	49.2	0.0	47.8	0.0	52.1	51.0	53.9	45.3	47.5	51.8	50.7	52.9	0.0	53.3	47.5	46.0	0.0	51.0	46.7	47.4	61.4	2000
	45.4	47.4	0.0	48.8	0.0	49.8	49.4	52.0	44.1	48.2	49.8	51.3	51.4	0.0	53.4	46.4	44.6	0.0	48.8	47.1	47.2	59.8	2500
	43.4	46.4	0.0	42.5	0.0	47.3	48.5	50.3	40.7	48.5	48.9	47.8	51.1	0.0	51.4	45.7	40.8	0.0	47.5	47.0	43.7	58.6	3150
	42.3	45.0	0.0	43.9	0.0	44.4	48.0	48.7	36.5	44.8	46.5	46.3	50.5	0.0	51.3	44.8	41.4	0.0	42.5	44.4	41.6	56.7	4000
	38.6	42.6	0.0	40.8	0.0	41.1	43.4	47.0	37.5	44.3	43.6	44.5	48.6	0.0	48.8	42.3	38.7	0.0	39.8	44.1	40.1	54.2	5000
LAmax$_{gear=2}$	59.9	58.0	0.0	58.9	0.0	62.8	60.2	64.7	56.1	60.5	61.7	59.7	63.9	0.0	61.9	58.5	58.5	0.0	58.6	58.2	59.9	70.4	
gear 3	19.0	0.0	0.0	0.0	0.0	20.5	15.5	11.6	0.0	0.0	0.0	13.6	0.0	0.0	13.9	0.0	0.0	0.0	13.5	15.7	4.9	17.0	31.5
	27.6	0.0	0.0	21.7	0.0	29.1	24.3	27.2	26.8	17.2	24.2	19.3	28.1	0.0	19.3	27.9	0.0	0.0	19.6	24.8	5.6	0.0	40
	31.9	31.8	0.0	16.2	0.0	28.4	27.0	29.8	22.0	30.9	24.8	25.8	0.0	0.0	26.8	28.8	0.0	0.0	19.1	23.5	23.1	40.4	50
	34.5	25.0	0.0	27.8	0.0	28.6	32.0	27.9	23.6	37.8	34.8	30.0	38.0	0.0	27.9	25.2	29.7	0.0	25.1	19.7	30.7	32.1	63
	35.5	34.5	0.0	32.2	0.0	34.2	40.8	27.4	10.8	31.1	31.3	28.4	0.0	0.0	27.6	36.3	36.2	0.0	41.6	30.0	27.8	33.0	80
	34.5	32.3	0.0	36.2	0.0	28.4	33.2	35.3	27.3	35.6	31.6	32.5	42.2	0.0	27.7	32.1	0.0	0.0	37.9	33.3	26.5	35.9	100
	35.7	27.3	0.0	32.9	0.0	33.4	33.5	29.8	22.4	25.2	22.7	30.2	43.4	0.0	26.5	35.9	34.9	0.0	32.1	27.7	29.5	35.4	125
	36.1	33.3	0.0	31.0	0.0	36.6	41.6	38.2	30.8	37.5	27.7	32.6	43.4	0.0	33.0	39.7	39.3	0.0	33.7	33.3	34.8	39.9	160
	42.0	34.9	0.0	34.6	0.0	42.4	37.6	43.5	34.2	38.4	37.6	35.6	40.6	0.0	38.4	38.3	43.5	0.0	27.0	34.9	39.5	45.3	200
	41.1	38.4	0.0	43.0	0.0	43.9	39.1	46.7	34.9	40.9	41.8	32.9	45.4	0.0	36.7	40.4	41.2	0.0	0.0	41.4	41.6	44.9	250
	41.8	42.0	0.0	38.6	0.0	45.0	39.0	48.3	42.2	34.5	43.5	37.9	44.4	0.0	36.6	42.3	43.6	0.0	43.7	41.5	35.6	47.7	315
	44.3	43.6	0.0	37.6	0.0	37.3	40.4	48.3	37.0	44.1	42.4	41.4	48.1	0.0	43.4	42.0	44.7	0.0	42.0	45.5	39.5	48.4	400
	44.9	43.8	0.0	35.6	0.0	46.8	24.0	48.1	42.0	43.8	39.9	42.4	51.1	0.0	43.7	44.9	46.5	0.0	42.7	46.7	40.9	48.1	500
	45.6	40.1	0.0	41.6	0.0	47.6	42.0	48.8	40.5	42.7	42.3	43.7	50.0	0.0	42.3	45.3	44.1	0.0	44.6	44.8	44.1	50.8	630
	44.8	39.0	0.0	43.9	0.0	49.1	44.7	45.0	43.7	47.1	47.0	42.3	49.7	0.0	45.3	40.4	46.9	0.0	47.2	42.4	45.2	53.9	800
	46.8	40.5	0.0	44.8	0.0	51.4	45.6	45.6	46.3	42.0	48.4	44.2	52.0	0.0	44.1	44.7	46.6	0.0	48.6	50.3	46.4	51.5	1000
	46.8	39.3	0.0	42.5	0.0	48.9	45.9	45.6	44.0	41.2	48.9	44.4	49.4	0.0	49.4	42.7	44.8	0.0	43.0	45.6	46.2	54.3	1250
	44.7	43.2	0.0	40.1	0.0	47.8	44.0	47.6	40.1	40.1	45.6	43.8	48.2	0.0	45.9	42.1	40.4	0.0	46.5	44.4	45.1	54.0	1600
	46.5	44.2	0.0	40.4	0.0	48.2	45.8	46.5	39.8	40.2	45.8	45.4	47.7	0.0	47.5	43.3	40.1	0.0	51.0	41.4	42.7	53.1	2000
	38.3	42.8	0.0	41.9	0.0	45.2	44.7	44.6	37.5	41.3	43.7	46.3	46.9	0.0	47.5	41.9	38.1	0.0	44.4	44.2	43.2	50.7	2500
	38.5	40.6	0.0	32.2	0.0	42.4	43.0	41.6	33.6	42.7	42.4	41.0	45.9	0.0	45.1	41.5	31.6	0.0	46.2	43.7	38.7	50.1	3150
	37.3	39.7	0.0	36.3	0.0	38.8	42.7	39.8	26.9	38.1	40.9	40.5	47.2	0.0	46.0	39.6	33.8	0.0	39.3	40.3	36.3	48.3	4000
	33.6	37.7	0.0	34.5	0.0	35.6	38.1	39.0	31.0	40.0	36.8	39.0	45.1	0.0	43.4	37.1	35.7	0.0	38.3	39.0	35.4	46.3	5000
LAmax$_{gear=3}$	55.8	53.3	0.0	52.6	0.0	58.3	55.1	58.0	52.5	54.1	56.3	54.4	60.3	0.0	56.8	54.4	55.3	0.0	57.1	56.3	54.6	62.7	

The investigated hybrid car with the number 17 reveals LAmax values of 58.5 and 55.3 dB(A), respectively. The car is equipped with a hybrid system of electric and diesel powered engines. Thus, the noise emission of this hybrid car is rather low for a diesel engine at a speed of 30 km/h, especially for the 3rd gear.

Summarizing, the choice of gear in the low speed range results in a strong influence to noise emission on propulsion noise and therefore constitutes a decisive factor when modelling traffic noise at lower speeds.

3.2 Effects of acceleration

In the low speed range acceleration is an important parameter of noise emissions causing substantially increased levels of propulsion noise [9]. It is important to note that acceleration events are not as common as vehicles passing at constant speed. The occurrence of acceleration events at low speeds is less than 15% [5]. In Figure 2 the total maximum noise levels (sum of rolling and propulsion noise level) of acceleration events at different driving styles are compared with the noise levels at a constant speed of 30 km/h.

On average, acceleration events were measured to account for an additional 6.3 dB to the median total noise level compared to events at constant speed. However, depending on the driving behaviour the additionally emitted noise may vary between 0 and 16.1 dB.

The range accounting for acceleration events is between 0 and 16.1 dB with a median of 6.3 dB.

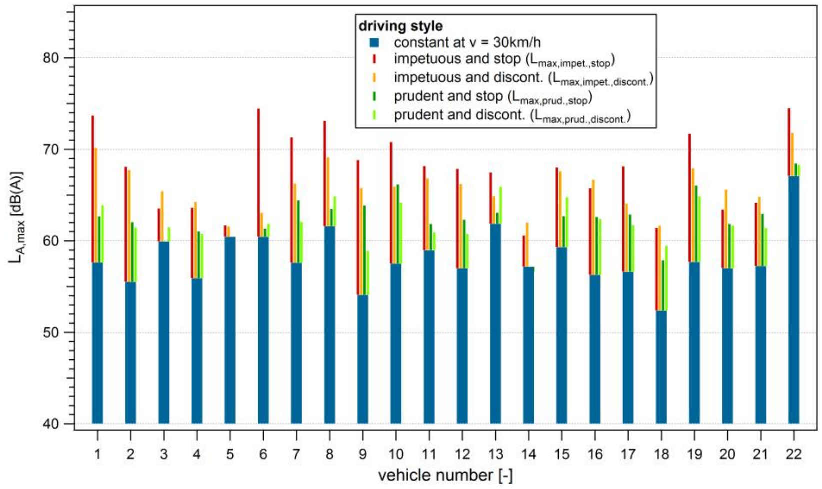

Figure 1: Maximum noise levels (sum of propulsion and rolling noise) per vehicle at a speed of 30 km/h ($LA_{max,v=30km/h}$; blue). Difference to $LA_{max,v=30km/h}$ due to an acceleration event from stop for the two different driving styles prudent and impetuous, $\Delta L_{max,prud.,stop}$ (green) and $\Delta LA_{max,impet.,stop}$, (red) respectively. And for the acceleration event while discontinuous driving for both driving styles, $\Delta LA_{max,prud.,discount.}$ (light green) and $\Delta LA_{max,impet.,discount.}$ (light red).

The acceleration event impetuous acceleration after stopping resulted in the largest difference ($\Delta LA_{max,impet.,stop}$) to $LA_{max,v=30km/h}$, for all vehicles. In general, the impetuous compared to the prudent driving style revealed on average for all vehicles a larger noise emission of about 4 dB. Taking into account the engine type into account, the petrol cars revealed larger ΔLA_{max} values (on average 2 dB) for all acceleration events compared to diesel cars. Comparing diesel to the hybrid cars, the $\Delta LA_{max,impet.,stop}$ and $\Delta LA_{max,prud.,stop}$ for hybrid cars are on average 4 and 1 dB(A), respectively, smaller than the diesel cars. However, for the discontinuous acceleration events the $\Delta LA_{max,impet.,discont.}$ and $\Delta LA_{max,prud.,discont.}$ for hybrid cars are almost equal to the ones of diesel cars. This may be explained by the combustion engine that was switched on during the discontinuous acceleration events but not during the events starting from a stop.

3.3 Dependency of rolling and propulsion noise on speed

To explore the impact of vehicle fleet changes on noise emissions, the noise generation at different speeds in the low-speed range for the main vehicle categories is investigated in this Section. The investigated vehicles are grouped on the basis of the engine and vehicle type. Five different groups are built: diesel cars, petrol cars, diesel light-duty commercial vehicle, hybrid cars and electric cars. The rolling (according to the road surface used in CNOSSOS [10]), propulsion and total noise for each group are shown in Figure 2 as a function of speed in the range of 1 to 60 km/h. The propulsion noise for hybrid cars (see Fig. 1d) is only based on vehicle number 17 (see Section 2.3). For the electric vehicles only the total noise is presented (see Fig. 1e), which can be assumed to be the rolling noise according to Section 2.3.

In all vehicle groups the propulsion noise arising from driving in the 1st gear reveals the highest noise emission and decreases with increasing gear. The propulsion noise in total was calculated according to the statistical survey of the effective gear-speed-driving behaviour in reality (see Section 2.2). Therefore, the propulsion noise features a characteristic shape in all the vehicle groups due to the weighting of the different gears. Up to a speed of 13 km/h the 1st gear is the most dominant gear and thus a rather strong increase in propulsion noise appears. At 13 km/h the propulsion noise seem to experience its 1st peak, which is characteristic for each vehicle group and will further on considered as the 1st-gear-peak. Between 13 to about 15 km/h 2nd gear becomes more dominant, leading to a decrease of the propulsion noise. From 15 km/h up to about 30 km/h the 2nd gear dominates and leads to an increase in propulsion noise. Nevertheless, the 2nd-gear peak is not as clear as the 1st gear-peak. The shape of the propulsion noise of all the vehicle groups is rather similar; however, its magnitude is different. The diesel light-duty commercial vehicles reveal rather large propulsion noise levels compared to the other vehicle groups with a 1st-gear peak of 66 dB(A). Compared to the diesel light-duty commercial vehicles, diesel passenger cars result in much lower propulsion noise levels having a 1st-gear-peak of 57 dB(A). Petrol cars show a 1st-gear-peak of 56 dB(A) which is slightly below the one of diesel cars. At higher speeds propulsion noise becomes relatively low compared to diesel cars (see also discussion in Section 3.1). The 1st-gear-peak for hybrid cars is also at 56 dB(A). However, this result needs to be treated with care, as the sample of hybrid cars was relatively small.

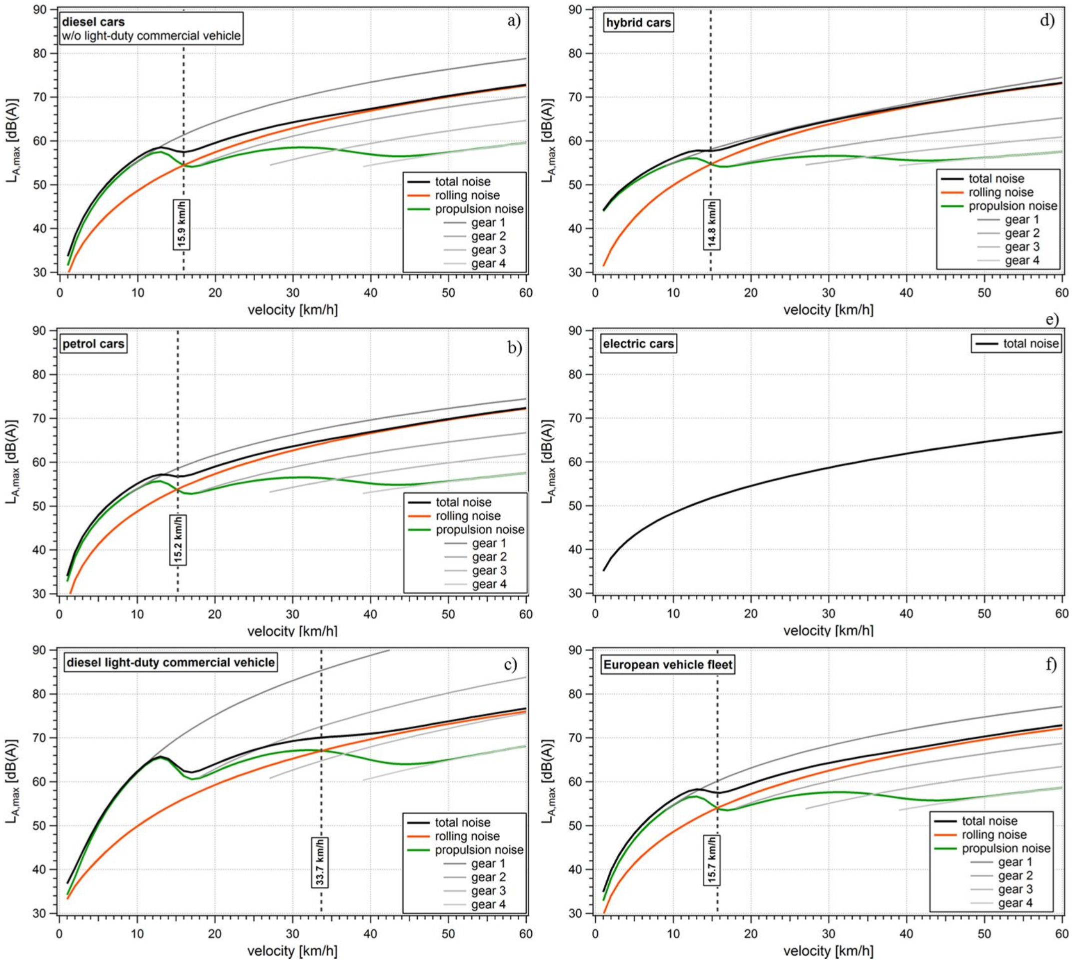

Figure 2: Rolling (red) and propulsion noise driving in gear 1, 2, 3, 4 (grey tones) and weighted gears (green) as well as total noise (black) from vehicle categories a) diesel cars, b) petrol cars, c) diesel light-duty commercial vehicle, d) hybrid cars, e) electric cars and f) European vehicle fleet [11], [12]. The speed at which the rolling noise becomes more dominant than the propulsion noise is indicated with a dashed black line. The rolling noise levels are referenced to the road surface used in CNOSSOS [10].

The speed at which the rolling noise becomes more dominant than the propulsion noise is called cross-over speed and indicated in Fig. 2 with a dashed line. The range of cross-over speeds for all vehicle groups is within 14.8 to 33.7 km/h. The lowest cross-over speed results for hybrid cars, which can be explained with the rather low propulsion noise at low speeds due to the electric engine. In general, a specific cross-over speed is difficult to define for hybrid cars since it is strongly depending on battery charge level, i.e. if the car is running on the electric or the combustion engine. Petrol and diesel cars show a rather similar cross-over speed with values of 15.2 and 15.9 km/h. The largest cross-over speed was found for diesel light-duty commercial vehicles having a value of 33.7 km/h.

In Figure 2e) the European vehicle fleet is shown with a composition of 53% petrol cars (incl. gas powered cars), 38% diesel cars, 1.4% hybrid cars, 0.7% electric cars and 6.9% light-duty commercial vehicle [11], [12]. It results in a 1st-gear-peak of 57 dB(A) and a cross-over speed of

15.7 km/h. This is rather low compared to previous studies showing cross-over speeds usually above 25 km/h for passenger cars [10], [13], [14]. However, for this study it was intended to investigate a more modern vehicle fleet to establish a model for present and future use. The average year of construction of the investigated vehicle fleet is 2011 with the oldest car being considered in 2002. Additionally the study [15] states that lower cross-over speeds are expected. Modern cars are equipped with more efficient and quieter engines resulting in a decrease of propulsion noise levels [16]. Therefore, lower propulsion noise levels resulted from this study compared to e.g. CNOSSOS [10] showing a crossover-speed of 29.7 km/h.

4. Conclusions

This study elaborated the noise emission of a modern vehicle fleet (average date of construction at 2011) at lower speeds. It analysed different influencing factors related to engine and tyre characteristics and differentiated between rolling noise and propulsion noise. In addition, the influence of acceleration and driving style were investigated.

It was found that petrol cars show slightly lower maximum noise levels compared to diesel cars at constant driving speeds. The opposite was found for acceleration events, where petrol cars seem to show a larger increase in propulsion noise during an acceleration event than diesel cars.

This study revealed significantly lower cross-over speeds between rolling and propulsion noise of around 15 km/h for petrol and diesel-driven vehicles than existing traffic noise emission models (the European model CNOSSOS assumes cross-over speed for light vehicles at 29 km/h). Hybrid cars revealed the lowest cross-over speed at 14.8 km/h. The study, moreover, showed that gear selection constitutes a decisive influencing factor which needs to be taken into account when modelling traffic noise emissions at speeds below 50 km/h.

The significant differences obtained for different vehicle categories highlights the need for taking into account future shifts in the vehicle fleet for accurate noise emission modelling.

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