DELIVERABLE 3.2.2

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	3.2	**Noise specifications for vehicle purchase and noise criteria for vehicle free access to Q-Zones**
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PU	Public	✓
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restrictec to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for the members of the consortium (including the Commission Services)	

Nature of Deliverable

R	Report	✓
P	Prototype	
D	Demonstrator	
O	Other	

SEVENTH FRAMEWORK PROGRAMME

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0 EXECUTIVE SUMMARY

0.1 OBJECTIVE OF THE DELIVERABLE

The objective of this study is to develop suitable noise criteria for vehicles to enter a quiet zone (Q-Zone) in a city. The study is restricted to passenger cars only.

0.2 DESCRIPTION OF THE WORK PERFORMED SINCE THE BEGINNING OF THE PROJECT

The following has been performed within this work package (WP 3.2.2):

- Studies regarding proper test method for type approval of passenger cars in urban areas with a focus on electric and hybrid cars
- Sound measurements on new hybrid and electric passenger cars
- Collection of noise emission data from normal passenger cars [1]
- Development of noise classifications covering the whole range in exterior noise from passenger cars based on the measured and collected noise data
- Proposal on suitable noise limit for a passenger car to be allowed free access in Q-zones

0.3 MAIN RESULTS ACHIEVED SO FAR

Sound measurements during type approvals of passenger cars should be performed according to the standard ISO 362:2007 (included in noise regulation ECE R51, method B). This standard gives a more adequate representation of real-world urban traffic noise compared to the earlier standard ISO 362:1998 (included in noise regulation ECE R51, method A).

Five different noise classes (A, B, C, D and E) covering the whole range in exterior noise from passenger cars according to ISO 362:2007 have been developed. Noise class A is the quietest class, while E is the noisiest class. The proposal is that a passenger car has to fulfil noise class A, i.e. **L_{urban} < 64 dBA**, in order to be granted free access to a Q-zone. This is about 8-10 lower noise levels compared to normal passenger cars during normal urban driving on urban main streets with speed limit 50 km/h. The reduction potential is higher on streets with lower speed limits (e.g. residential streets), due to the quiet engine that becomes more and more apparent towards lower speeds. However, studies mentioned in section 2.2.2 show that people are less annoyed along residential streets with speed limit 30 km/h compared to main streets with speed limit 50 km/h. Therefore, the most important thing is to reduce the exterior noise at roads rated at 50 km/h.

0.4 EXPECTED FINAL RESULTS

Over time, the main goal with the CityHush project is assumed to be fulfilled by implementing noise specifications for vehicles in Q-zones. However, similar noise specifications must be developed for other vehicles as well, e.g. light trucks, garbage trucks, busses and motorcycles (mopeds). Furthermore, other noise reduction techniques (presented in other Deliverables), such as low noise tyres and low noise road surfaces etc. must be developed and implemented in the zone in order to fully achieve the main goal.

0.5 POTENTIAL IMPACT AND USE

The proposed testing method (ECE R51, method B) during type approval has been used by manufactures since 2007 and is therefore already a well-known noise testing method. However, some small changes in the full acceleration test may be needed when testing hybrid and electric passenger cars in order to include all relevant noise sources in an adequate way.

By updating the noise access limits due to the current noise data for quiet electric vehicles approximately every year or bi-annually, an up-to-date noise limit for access to Q-zones will always be available for electric or hybrid vehicles. More studies should therefore be performed in this area on a regularly basis.

0.6 PARTNERS INVOLVED AND THEIR CONTRIBUTION

The partners involved in this study are:

- Acoustic Control (ACL)
- Head Acoustic (HAC)
- Stockholm Environmental Protection Agency (SEP)
- Traffic & Public Transport Authority (TPTA) in Gothenburg

ACL have been in contact with HAC for technical discussions and exchange in measurement data. ACL have also been in contact with SEP regarding access to suitable electric vehicles for sound measurements and regarding electric vehicles in Sweden in general. All partners have given valuable input and remarks regarding the content in this report.

0.7 CONCLUSIONS

The following conclusions are given in this study:

- Type approval according to ECE R51 method B (ISO 362 :2007)
- Full acceleration test from 30 km/h instead of 50 km/h for electric passenger cars with weak engines (e.g. PMR < 40). More studies should be made in this area
- A passenger car that is granted free access in Q-zones has to fulfil **L_{urban} < 64 dBA** (i.e. noise class A). This is about 8-10 lower noise levels compared to normal passenger cars during normal urban driving on urban main streets with speed limit 50 km/h. This noise limit is likely to imply that only pure electric vehicles are granted free access
- Similar noise limits should be developed for other vehicle categories as well in order to consider all types of vehicles in a Q-zone and to acchieve the needed noise reduction

1 INTRODUCTION AND OBJECTIVE

The main goal with the CityHush project is to present solutions that reduce the overall traffic noise levels in urban areas by 10-20 dBA-units. One possible way to achieve this is to only allowing quite hybrid/electric vehicles free access to certain quiet zones (Q-zones) in the city. The objective of this study is therefore to develop suitable noise criteria for vehicles to be allowed free access in Q-zones. However, this study is restricted to passenger cars only.

2 TESTING METHODS FOR EXTERIOR NOISE TYPE APPROVAL

A universal and functional noise specification requires a proper noise testing method that considers the actual driving conditions and provides the basis to evaluate new propulsion technologies like hybrid and pure electric vehicles.

2.1 ECE REGULATION 51, METHOD A

The current noise Regulation No 51 (R51) of the Economic Commission for Europe (ECE) has been in force since 1970 (Directive 70/157/EC) with several amendments since then. The measurement method is based on ISO 362:1998 and seeks to measure the highest noise levels produced in urban traffic with a focus on driveline noise, i.e. full throttle acceleration in urban areas. Therefore, the test method is based on a full throttle acceleration test starting from 50 km/h or less, depending on the vehicle category.

Since the technical design of vehicles has changed significantly over the last decade, the correlation between the test conditions for type approval and the conditions for normal urban driving has gradually decreased. New test conditions were therefore required to be more representative of normal urban driving behaviour in order to affect noise exposure in urban areas more efficiently.

2.1.1 Limit values

The regulated limit has been strongly reduced since the start in 1970, see Figure 2.1 below. However, almost no noise level decrease has been seen in real urban traffic. Note that the limit value for passenger cars is 74 dBA.

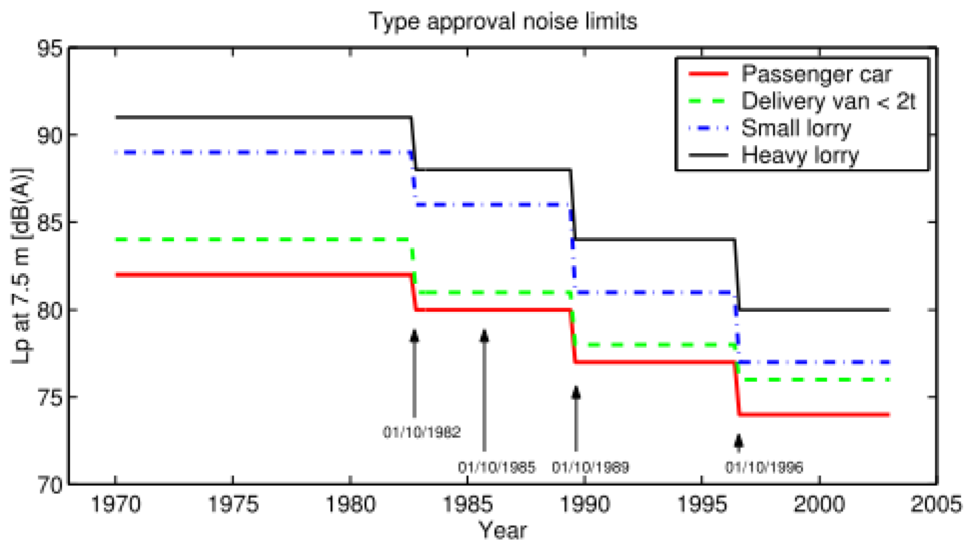


Figure 2.1 Historical development in EU type approval noise limits based on ECE R51 method A. The figure is taken from reference [3] page 51.

2.2 ECE REGULATION 51, METHOD B

The new ECE R51 method, based on ISO 362:2007, was prepared by WG42, a joint workgroup of ISO TC43/SC1 "Noise" and ISO TC22 "Road vehicles" and amended by WP29 in 2007 to be implemented in Directive 2007/34/EC. Development and evaluation were notably carried out in 2004 for technical accuracy and practical considerations by over 180 vehicles included in a first monitoring test program. In 2007/2008 the European Commission launched a new monitoring procedure for 2 years application in order to establish new limit values to be applied for the new test method B. During that time, the noise tests during type approval were measured according to the current method A as well as the new method B.

The measurement procedure in method B is based on an estimation of partial throttle operation at 50 km/h for light vehicles (M1, N1 and M2<3.5t) and at 35 km/h for heavy vehicles (M2>3.5t, N2, N3 and M3) which represents normal urban driving behaviour. For light vehicles, it seeks to approximate real partial throttle operation with a weighted average of a wide-open throttle test (wot) from 50 km/h with a constant speed test at 50 km/h. It ensures a better consideration of all noise sources emitted by road vehicles in urban traffic than the current method. Therefore, a decrease of limits regarding this new method will affect noise exposure in urban areas more efficiently than method A. It also provides the basis to evaluate new propulsion technologies like hybrid and fuel cell vehicles in a technological neutral manner.

2.2.1 Proposal for new vehicle categories and new limit values

The European Automobile Manufacturers' Association (ACEA) gave a proposal on new vehicle subcategories and new limit values in August 2010 [2] based on the new collected monitoring data from method B. Further information can be found in reference [2].

Table 2.2 Proposal for new subcategories and equivalent limit values. The table is taken from reference [2] page 9.

Category	Subcategory		Equivalent limit values in dB(A)	
			On Road	Off Road 1)
M1	M1-1	pmr <125 kW/t	72	74
	M1-2	125 kW/t < pmr <= 150 kW/t	73	74
	M1-3	pmr > 150 kW/t	75	75
N1/M2-A	N1/M2-A1	GVM <= 2500 kg	72	74
	N1/M2-A2	GVM > 2500 kg	74	75
N2/M2-B	N2/M2-B1	rated speed > 3000 min^{-1}	76	77
	N2/M2-B2	rated speed <= 3000 min^{-1}	78	79
N3	N3-1	2 axles, Pn <= 180 kW	79	80
	N3-2	2 axles, 180 kW < Pn <= 250 kW	81	82
	N3-3	2 axles, Pn > 250 kW	82	83
	N3-4	> 2 axles	84	85
M3	M3-1	Pn < 180 kW	76	77
	M3-2	180 kW < Pn <= 250 kW	78	79
	M3-3	Pn > 250 kW	80	81

1) off road as defined in R.E.3 and in addition have a wading depth exceeding 500 mm and a hill climbing ability exceeding 35°

2.2.2 Comments on the new test method B applied on hybrid/electric vehicles

The WG42 committee has had access to extensive in-use data to determine the actual driving behavior from light duty vehicles in urban traffic. To establish the operation criteria in method B, WG42 used the in-use vehicle data which showed that the most traveled speed is 50 km/h in urban areas [5]. Furthermore, a traffic noise study [6] revealed that 73 % of the annoyed people lives along main streets with speed limit 50 km/h, while 23 % lives along residential streets with speed limit 30 km/h. The test speed for light duty vehicles were therefore set at 50 km/h.

The main idea with the wot (wide open throttle) test from 50 km/h is to simulate a worst-case-scenario with a focus on driveline noise, while the idea with the constant speed test at 50 km/h is to focus on tyre/road noise. The weighted average (L_{urban}) is then a combination of both driveline and tyre/road noise so that all relevant noise sources are considered. However, this may not be the case for low noise vehicles with a weak engine, i.e. hybrid or pure electric vehicles.

Measurements reveal that for electric vehicles with a low power-to-mass ratio[1] the main focus at wot test from 50 km/h is on tyre/road noise instead of the driveline noise due to the quiet driveline. The weighted average (L_{urban}) is then only considering tyre/road noise. This may be correct for urban traffic conditions at main streets with speed limit 50 km/h and with very few traffic lights. However, it does not give a fair picture of the noise reduction potential on streets where the acceleration phase normally starts from speeds below 50 km/h, i.e. main streets with speed limit 50 km/h and with lots of traffic lights or residential streets with speed limit 30 km/h. A wot test with a start speed below 50 km/h gives more room for the driveline noise. Therefore, we recommend that the wot test for electric cars are to be performed at a lower start speed, e.g. 20 km/h.

[1] Dimensionless quantity used for calculation of acceleration according to the equation: PMR = Pn/m x 1000 kg/kW, where Pn is the engine power in kilowatts and m is the test mass in kilograms.

3 MEASURED AND COLLECTED NOISE DATA FROM PASSENGER CARS

Sound measurements on passenger cars (M1) have been performed according to ECE R51 method B based on ISO 362-1:2007. Measurements on one hybrid and four pure electric cars were performed by ACL in June 2011. Further measurements on hybrid and electric passenger cars have been performed by HAC in July 2011 focusing on seperating driveline and tyre/road noise. Detailed results from these measurements are presented in appendix 1 and 2. Noise emitted from 34 normal passenger cars were collected from measurements performed by the SAE Cooperative Research Program [1].

The measured and the collected noise data are summarised in Figur 3.1 below. It presents the constant speed test at 50 km/h (L_{crs}), the wide-open-throttle test from 50 km/h (L_{wot}) and the final result, L_{urban}, which is calculated as a weighted average of L_{wot} and L_{crs} in order to simulate real urban driving conditions and to include all relevant noise sources.

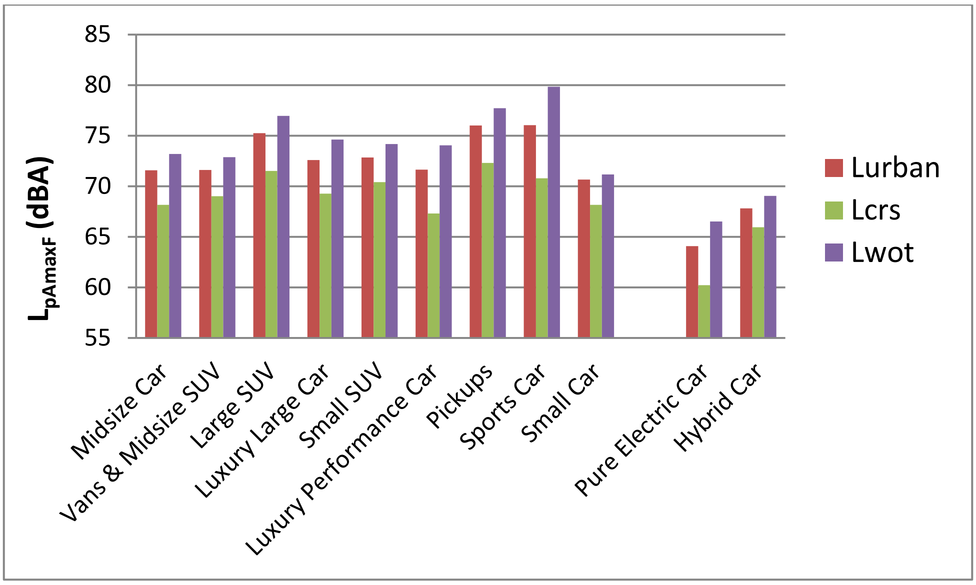


Figure 3.1 Measured and collected exterior noise data from passenger cars according to ECE R51 method B (ISO 362-1:2007).

The results presented above show that electric and hybrid passenger cars emits about 5-10 dBA lower noise levels compared to normal passenger cars during normal urban driving on a urban main street with a speed limit of 50 km/h and with few traffic lights.

A question is what L_{urban} levels we would have obtained with 20 km/h as starting speed instead of the start speed 50 km/h. We have performed a careful review of the L_{urban} level compared to the levels obtained for constant speed test and wot test fully carried out according to the standard procedure in ISO 362:2007. It is then revealed that we obtain a value of the L_{urban} level that is very close to the pure logarithmic average of the constant speed test and the wot test.

If we use this finding in order to obtain an L_{urban} level that corresponds to what would have been obtained if using 20 km/h as start speed instead of 50 km/h it is revealed that a 1 dBA unit lower level would be obtained for pure electric cars (like Mitsubishi iMiev, Citroen C-Zero and Peugeot iOn which all have a PMR=39). L_{urban} for Toyota Prius will be 2 dBA-units lower and for FIAT 500 EVadapt the L_{urban} level would be about 3 dBA-units lower since FIAT 500 EVadapt has very low driveline noise contribution due to the low PMR value that is only PMR=20.5 compared to PMR=39 e.g. for iMiev.

4 EXTERIOR NOISE CLASIFICATION

4.1 NOISE CLASSES FOR PASSENGER CARS

Five different noise classes (A, B, C, D and E) covering the whole range in exterior noise from passenger cars according to ISO 362:2007 have been developed. Noise class A is the quietest class, while E is the noisiest class. Information about these noise classes are given in the table below.

Table 4.1 Five different noise classes covering the whole range in exterior noise from passenger cars.

Noise class	Noise limit ISO 362:2007 (L_{urban})	Typical passenger car types
A	<64 dBA	Pure electric cars
B	64 - 68 dBA	Hybrid cars
C	68 - 72 dBA	Normal passenger cars
D	72 - 76 dBA	Large passenger cars
E	>76 dBA	Sport cars and pickups

The upper limit of noise class A-D and the measured and collected exterior noise data (L_{urban}) are presented in Figure 4.1 below. Note that noise class C corresponds to the proposed equivalent limit for M1-1 shown in Table 2.2 (L_{urban} 72 dBA).

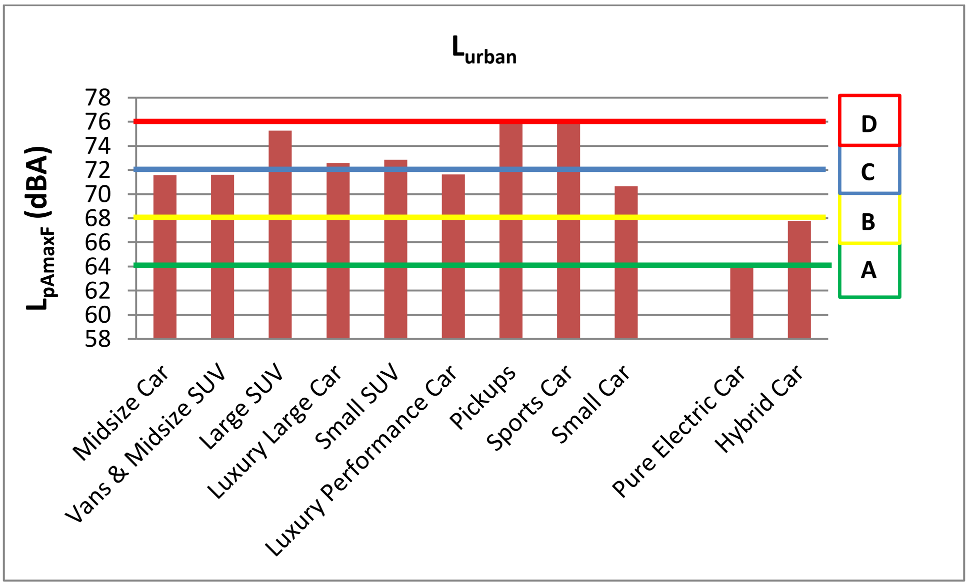


Figure 4.1 Measured and collected exterior noise data (L_{urban}) from passenger cars including the upper limit of noise class A-D.

4.2 PROPOSAL ON NOISE LIMITS FOR PASSENGER CARS TO ENTER Q-ZONES

There exists up to now no definition on what qualities regarding noise that shall be required from a vehicle in order to be considered an enough "quiet vehicle" (presented in Deliverable 3.2.1) and thus free access could be granted to a Q-zone.

The proposal is that a passenger car has to fulfil noise class A, i.e. **L_{urban} < 64 dBA**, in order to be granted free access to a Q-zone, see Table 4.1 and Figure 4.1. This is about 8-10 lower noise levels compared to normal passenger cars during normal urban driving on urban main streets with speed limit 50 km/h. The reduction potential is higher on streets with lower speed limits (e.g. residential streets), due to the quiet engine that becomes more and more apparent at towards lower speeds. However, studies mentioned in section 2.2.2 reveal that people are less annoyed along residential streets with speed limit 30 km/h compared to main streets with speed limit 50 km/h. Therefore, the most important thing is to reduce the exterior noise at 50 km/h.

A reduction by 10 dBA at higher speeds (> 50 km/h) will only be achieved if measures are taken to reduce the tyre/road noise. One way of doing this is to use the *"Goodyear method"*. This method is based on selection of very quiet tread patterns which are assumed to be run on very smooth road surfaces with max stone size < 5 mm. This would also require a ban for studded tyres in certain areas e.g. in the Nordic countries like Sweden Norway and Finland.

Note that there are probably only pure electric cars that can be granted free access with the proposed noise limit.

4.3 OTHER TYPES OF VEHICLES IN Q-ZONES

This study only handles passenger cars in the zone. However, there is a need also for transportation of goods to shops and grocery stores in the zone, for garbage collection as well as for public transportation with buses. For this reason, examples of hybrid electric light truck and garbage trucks (hybrid garbage collecting trucks were recently demonstrated by Volvo Truck in Göteborg) as well as hybrid electric busses must be studied and documented. In 2008, ACL performed similar studies on hybrid city buses within another project. These results are though not presented in this report.

5 REFERENCES

[1] Moore, D.B. *The revised ISO 362 standard for vehicle exterior noise measurement*, Article in *Sound and Vibration*, Oktober 2006

[2] ACEA, *Monitoring procedure in the vehicle noise regulation*, Final report, 27 August 2010

[3] TNO report, *VENILOVA – Vehicle Noise Limit Values – Comparison of two noise emission test methods – Final report*, 30 March 2011

[4] ISO 362-1:2007, *Measurement of Noise Emitted by Accelerating Road Vehicles – Engineering Method – Part 1 : M and N categories*

[5] Steven, H. *Investigations on Improving the Method of Noise Measurement for Powered Vehicles*, Report Number 10506067 by order of the Germany Federal Environmental Agency, August 1999

[6] Steven, H. *Further Noise Reductions for Motorized Road Vehicles*, Presentation within the Workshop of the German Federal Environmental Agency, September 2001

APPENDIX 1

SOUND MEASUREMENTS ON HYBRID AND ELECTRIC VEHICLES BY ACL, JUNE 2011

Test vehicles

Vehicle	Gasoline Engine	Electric Motor	Transmission	Dimensions	Kerb weight	Tyres
Toyota Prius	1,5L 4-Cyl. 73 kW (98 hp), 145 Nm	AC-motor, 50 kW, 400 Nm	Automatic (ECVT)	Length: 4450 mm Width: 1725 mm	1400 kg	Primacy Pilot 195/55R16 (87V)
Mitsubishi iMiEV	-	AC-motor, 47 kW (64 hp), 180 Nm	Automatic, 1 speed	Length: 3475 mm Width: 1475 mm	1120 kg	Dunlop Enasave 2030 Front: 145/65R15 Rear: 175/55R15
Fiat 500 EVadapt	-	AC-motor, 24 kW (nominal)	Automatic, 1 speed with 3 driving programs (orginal gearbox limited to 1,2,3 and reverse)	Length: 3546 mm Width: 1627 mm	1100 kg	Continental ContiEcoContact 3 175/65R14
Peugeot iOn	-	AC-motor, 47 kW (64 hp), 180 Nm	Automatic, 1 speed	Length: 3475 mm Width: 1475 mm	1120 kg	Dunlop Enasave 2030 Front: 145/65R15 Rear: 175/55R15
Citroen C-Zero	-	AC-motor, 47 kW (64 hp), 180 Nm	Automatic, 1 speed	Length: 3475 mm Width: 1475 mm	1120 kg	Dunlop Enasave 2030 Front: 145/65R15 Rear: 175/55R15

Toyota Prius:

Mitsubishi iMiEV:

Fiat 500 EVadapt:

Peugeot iOn:

Citroen C-Zero:

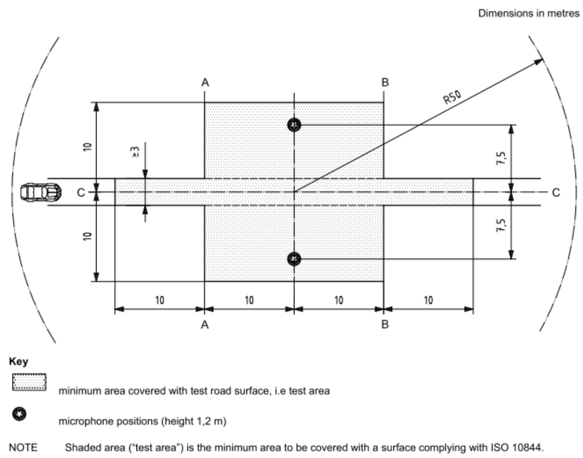
Test Site

Sound measurements were performed on a karting track in Järfälla, Sweden (Gokartvägen 1, Järfälla) with a dense bitumen asphalt layer with maximum stone size 8 mm (ABT 8).

Measurements

Procedure and setup

The measurements were performed 2011-05-16 and 2011-06-27 according to ISO 362:2007 but with an extended measurement program in order to extract the tyre/road noise and the driveline noise from the measured data. According to ISO 362:2007, two test are to be performed, one constant speed test (cruise-by) at 50 km/h and one wide-open-throttle test (wot) with the start speed 50 km/h. In the extended measurement program the constant speed test is performed at speeds 15, 20, 25, 30, 40 and 50 km/h. The wot test is performed with start speeds 20, 30 and 50 km/h. Each test is measured 3 times at each speed. The vehicle speed was recorded with a GPS speed and position logging system (Race Technology).



Passenger cars contain several sound sources contributing to the total noise level. However, for urban driving (low vehicle speeds) the main sound sources are confined to the driveline and the tyre/road interaction only. We can therefore separate the total noise level into driveline noise and tyre/road noise. The total noise at higher velocities mainly consists of tyre/road noise. Due to this knowledge and a constant velocity exponent assumption, we can separate the tyre/road noise from the total level. The driveline noise is then extracted by subtracting the tyre/road noise from the total noise level.

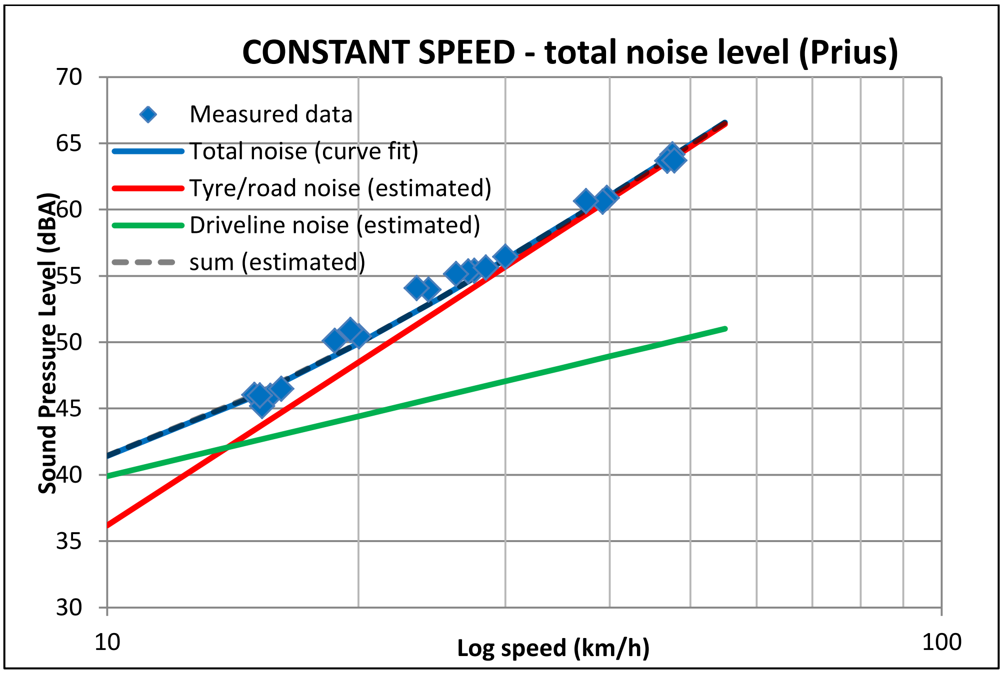
The subject of tyre/road noise has been widely studied for many years. It has been shown that the peak tyre/road noise in dBA of a coasting vehicle measured at 7,5 m is related to the vehicle speed by the following expression: **LpA = m log(v) + constant**, where the LpA is the peak noise, v is the vehicle speed (km/h) and m is a constant (the slope in a logarithmic diagram). We assume that the driveline follows the same expression during the constant speed test. The driveline noise is then adjusted so that the calculated sum (tyre/road + driveline) coincide with the measured data . The estimated tyre/road noise during wot test is the tyre/road noise from the constant speed test added with 2 dB due to slightly higher speed when passing the microphone and due to a higher torque load onto the tyres.

Instrumentation

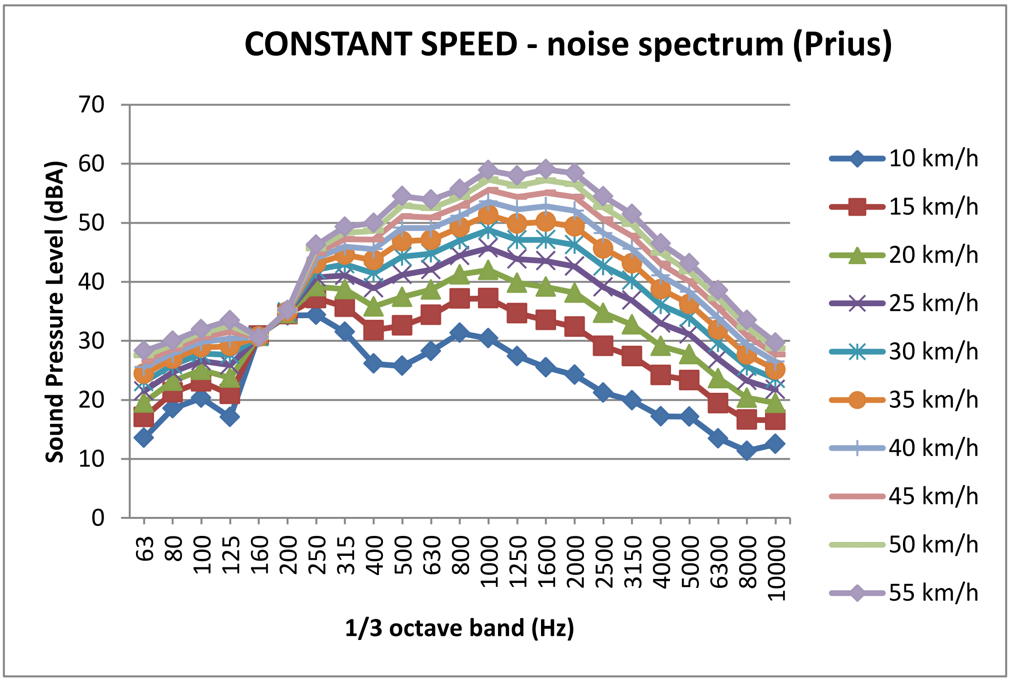
Instruments and equipment used during the measurements are listed in the table below.

Equipment	**Brand**	**Type**
12-channel signal analysis system	Brüel & Kjaer	Portable PULSE
5 microphones	Brüel & Kjaer	4189 A21
Microphone wind shields	Brüel & Kjaer	
Sound level calibrator	Norsonic	
GPS speed and position logging system	Race Technology	DL1

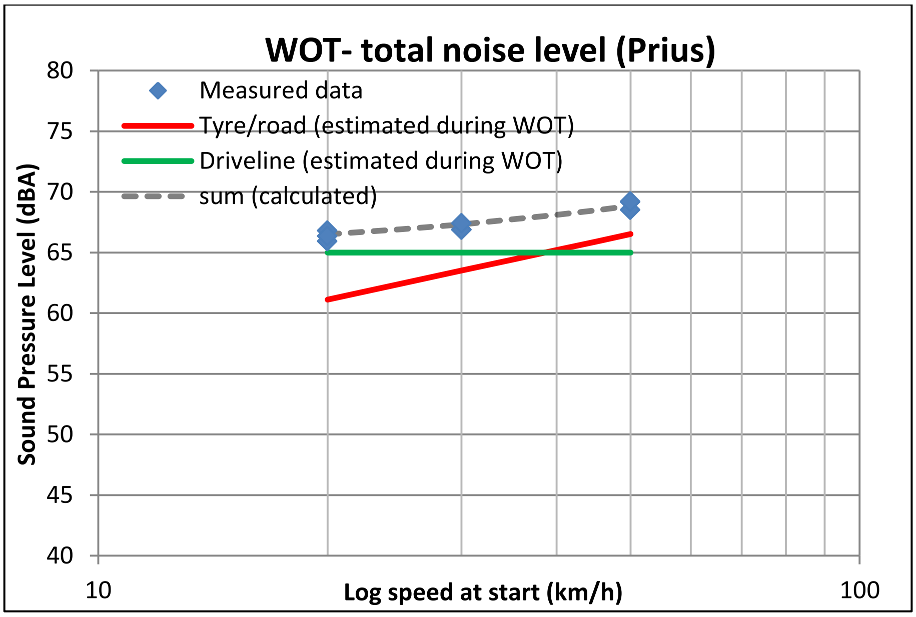
Results



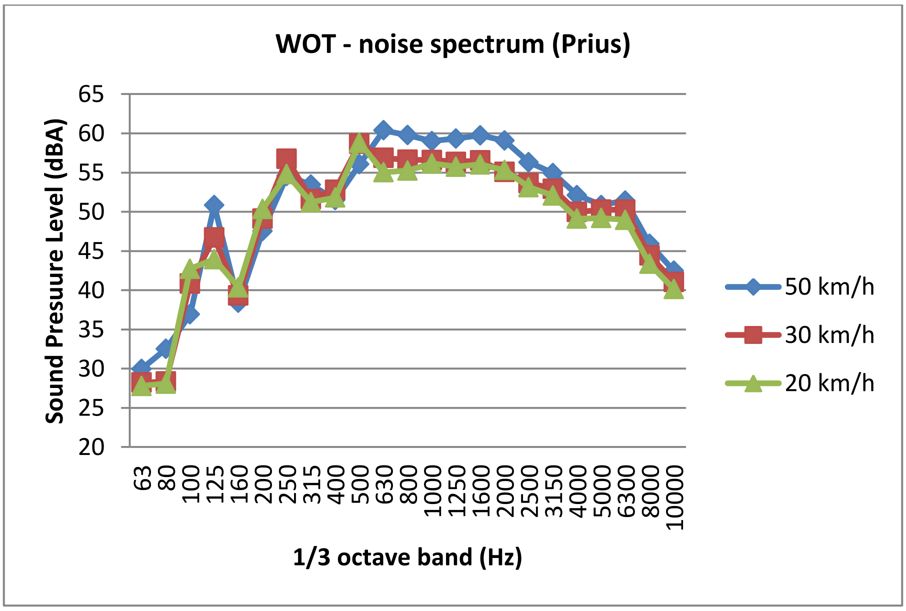
The car was driven at EV-mode under 25 km/h. The estimated tyre/road noise and driveline noise are equally strong slightly below 15 km/h. The driveline noise is dominating below 15 km/h while the tyre/road noise is dominating above 15 km/h ($LpA_{tyre/road}$ = **40.8 log(v) – 4.7**, $LpA_{driveline}$ = **15.0 log(v) + 24.9**). This means that the acoustic power around 1000-2000 Hz at higher speeds is mainly tyre/road noise (se diagram below). At lower speeds, a peak around 250 Hz starts to appear which may be due to the driveline. Note that the peak at 250 Hz and 1000 Hz are equally strong at about 15 km/h which strengthen the assumption that the driveline and the tyre/road noise cross each other at about 15 km/h. Furthermore, the velocity slope at 250 Hz is m = 16 and m = 41 at 1000-2000 Hz which are similar to the velocity slope in the total noise analysis. The velocity slope decreases above 2500 Hz.

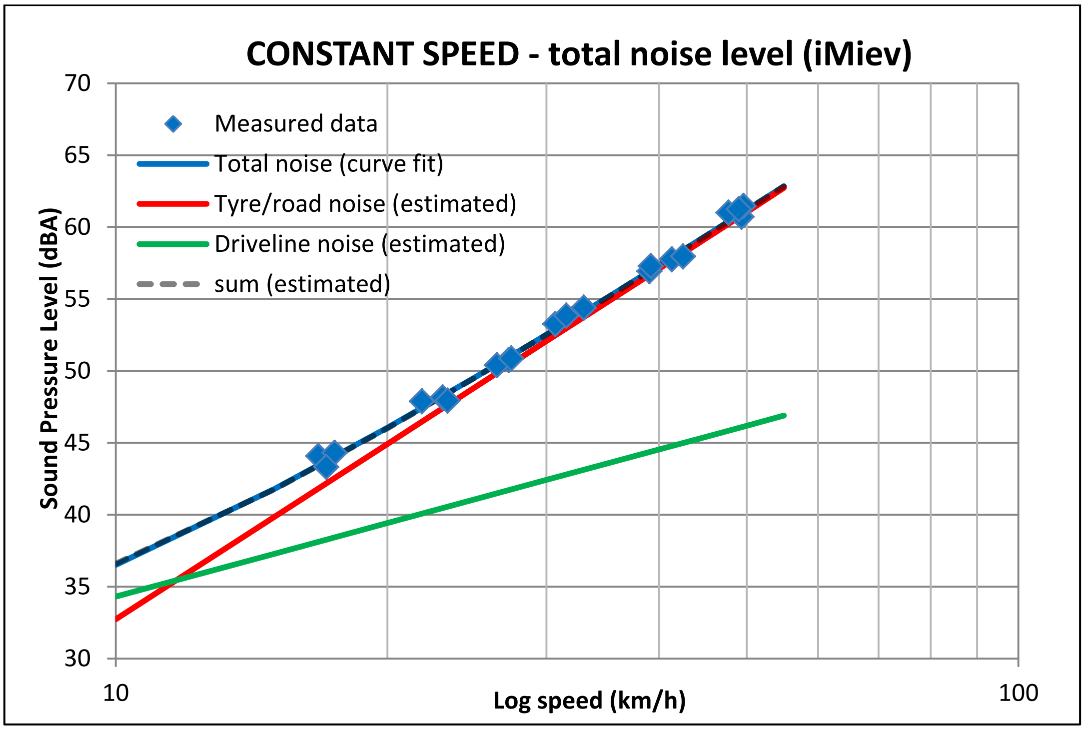


WOT – total noise level (Prius)		
Start speed	**Sound Pressure Level**	
50 km/h	69 dBA	72 dBC
30 km/h	67 dBA	71 dBC
20 km/h	66 dBA	71 dBC

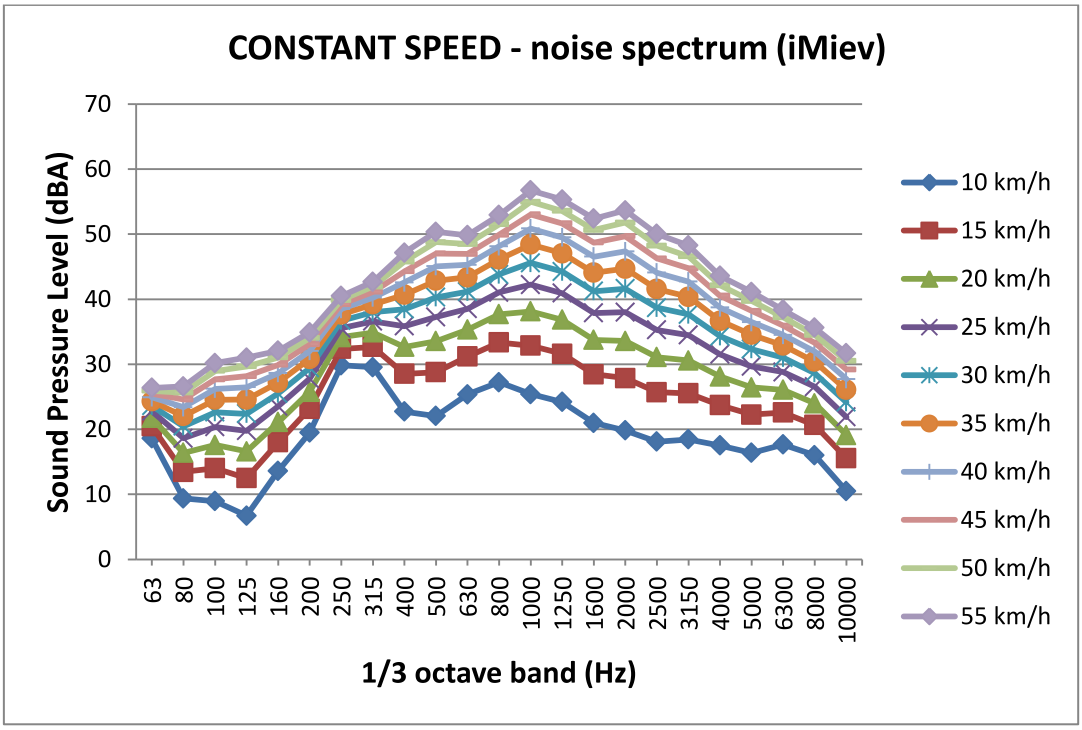


Note that the tyre/road noise is higher than the driveline noise at wot-test 50 km/h, while the driveline noise is dominating at lower start speeds. The peaks at 125, 250 and 500 Hz are due to the gasoline engine.

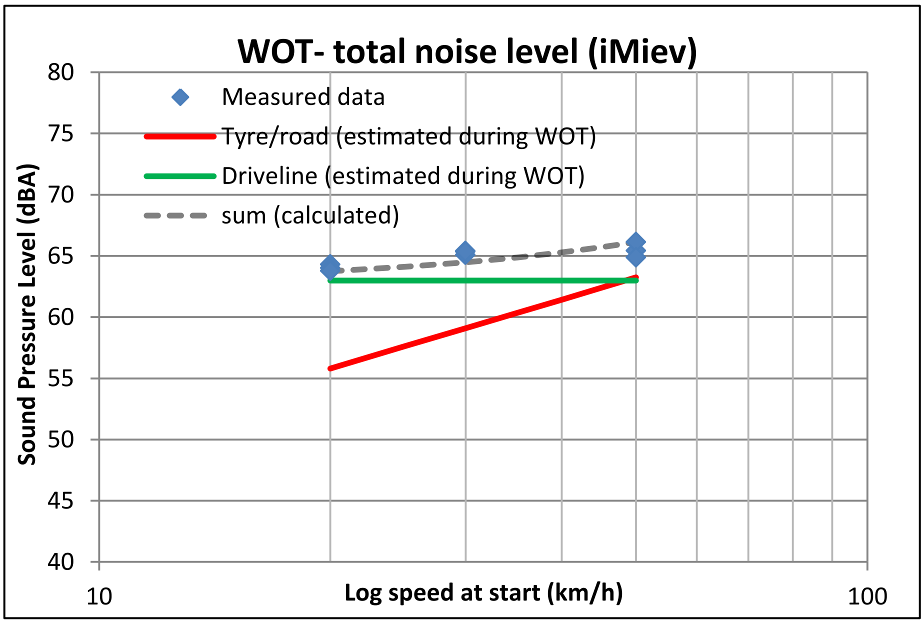




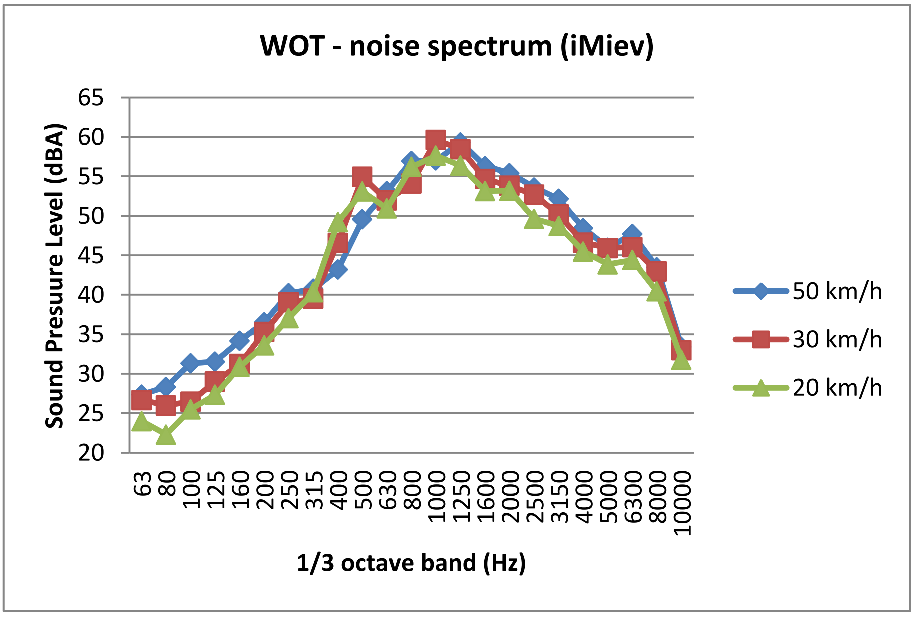
The estimated tyre/road noise and driveline noise are equal between 10-15 km/h ($LpA_{tyre/road}$ = **40.5 log(v) – 7.8**, $LpA_{driveline}$ = **17.0 log(v) + 17.3**). Note that the same trend can be seen in the spectrum with the tyre/road peak at 1000 Hz at high speeds and a driveline peak at 250 Hz at low speeds. The velocity slope at 250-315 Hz is m = 16 and m = 42 at 1000 Hz which are similar to the velocity slope in the total noise analysis. The velocity slope decreases above 2500 Hz.

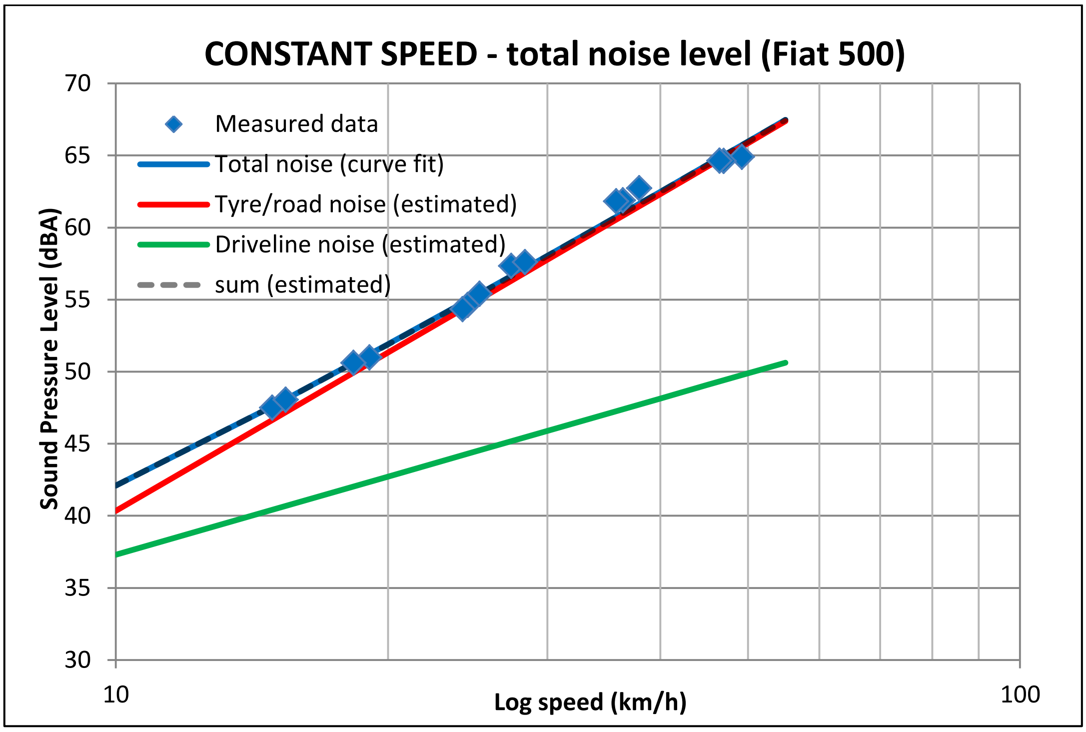


WOT – total noise level (iMiev)		
Start speed	**Sound Pressure Level**	
50 km/h	66 dBA	66 dBC
30 km/h	65 dBA	66 dBC
20 km/h	64 dBA	65 dBC

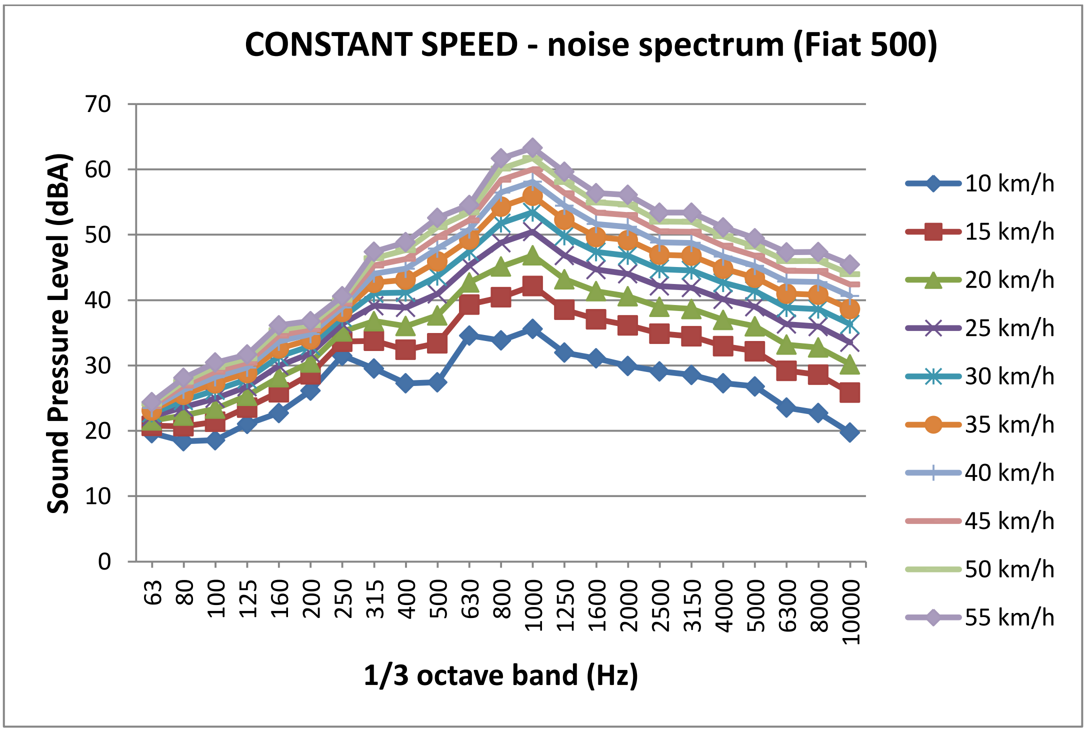


Note that the tyre/road and the driveline noise is almost the same at 50 km/h, while the driveline noise is dominating at lower start speeds. Note also that there is almost no difference between dBA and dBC levels which indicates that there is no significant low frequency content and that the energy is confined to the higher frequency regions. This is shown in the frequency diagram below with a significant peak around 1000 Hz.

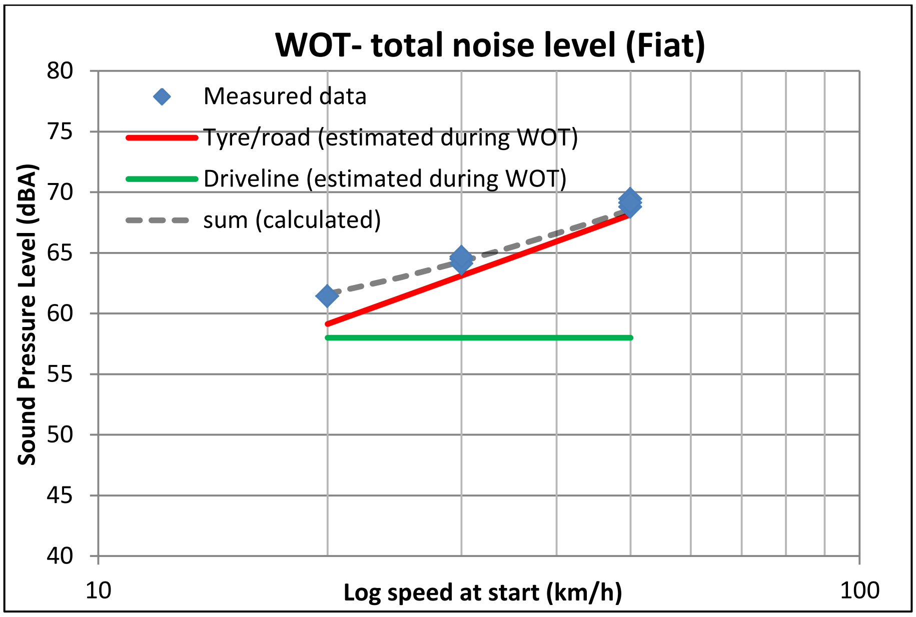




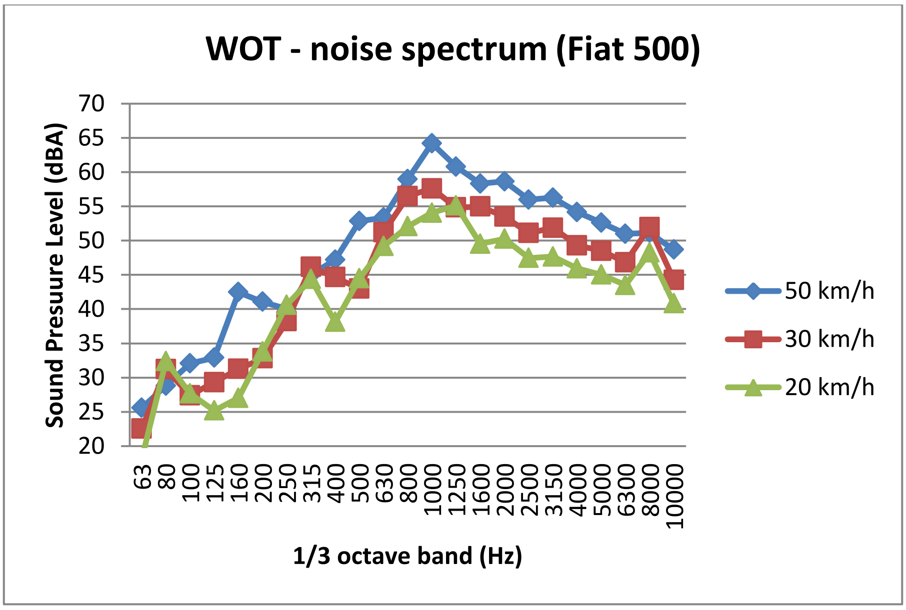
The measurements on Fiat 500 EVadapt were performed in the morning with a slightly wet road surface. The tyre/road noise is higher than the driveline noise at every speed ($LpA_{tyre/road}$ = **36.5 log(v) + 3.8**, $LpA_{driveline}$ = **18.0 log(v) + 19.3**). Note that the tyre/road peak at 1000 Hz is dominant at every speed. Note also that the velocity slope is not decreasing above 2500 Hz which indicate that the road surface was wet. According to measurements by VTI in Sweden [Sandberg 2002], a wet road surface increases the noise level above 2000 Hz. Therefore, noise above 2000 Hz has been neglected in the total noise analysis with a reduction of about 1 dBA. The velocity slope at 250-315 Hz is m = 19 and m = 38 at 1000 Hz which are similar to the velocity slope in the analysis of total noise.

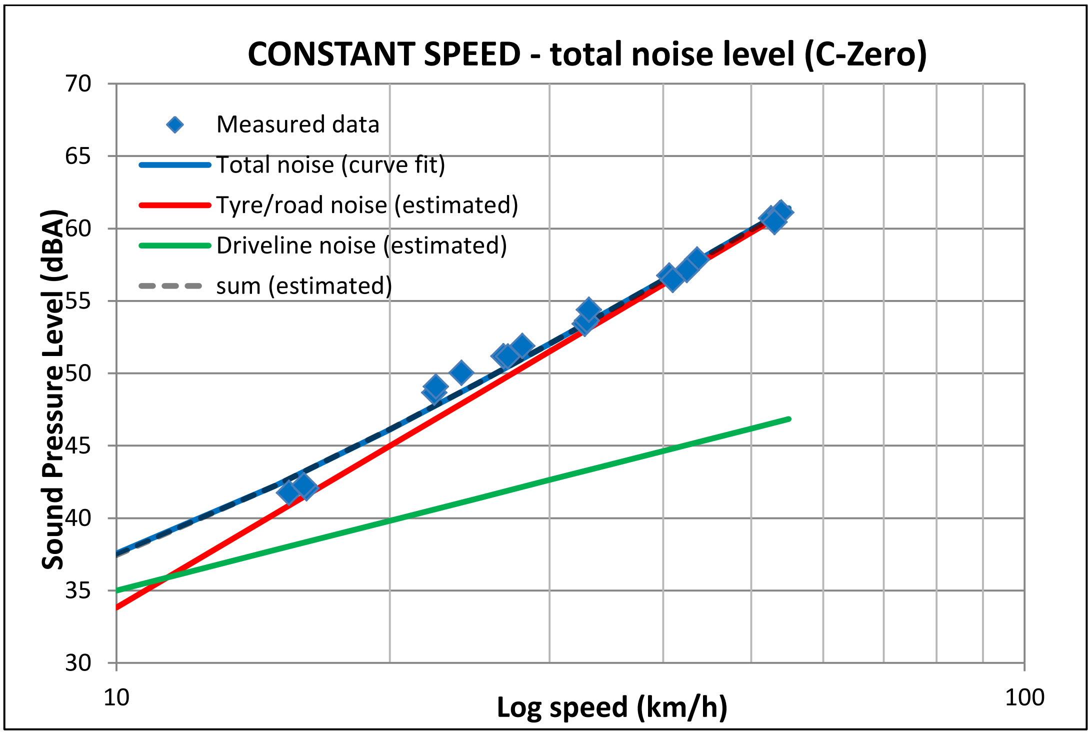


WOT – total noise level (Fiat)		
Start speed	**Sound Pressure Level**	
50 km/h	69 dBA	70 dBC
30 km/h	64 dBA	65 dBC
20 km/h	61 dBA	63 dBC

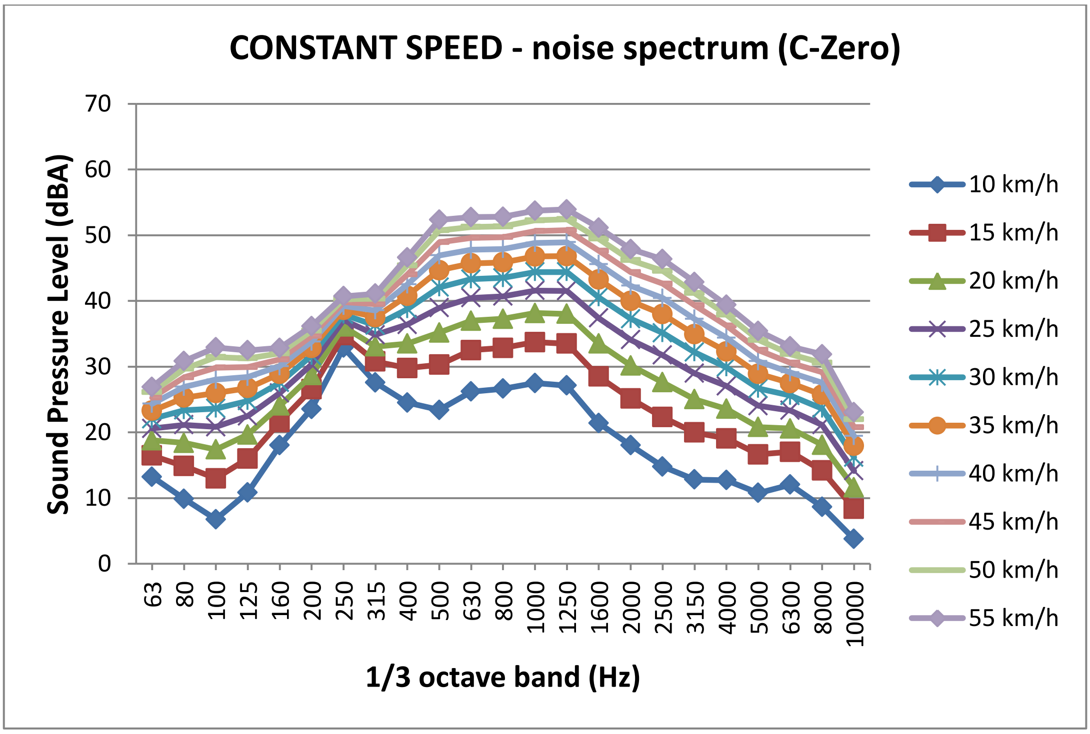


The car was driven in gear nr. 2 (urban driving). Note that the total noise level at is dominated by the tyre/road noise, especially at start speeds 30 and 50 km/h. The driveline noise is rather low due to the weak engine.

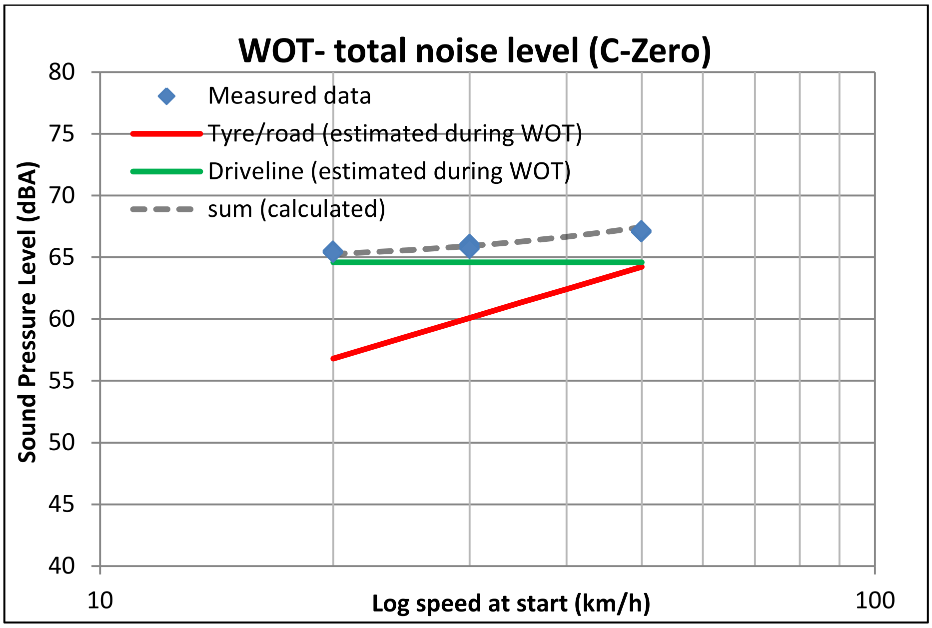




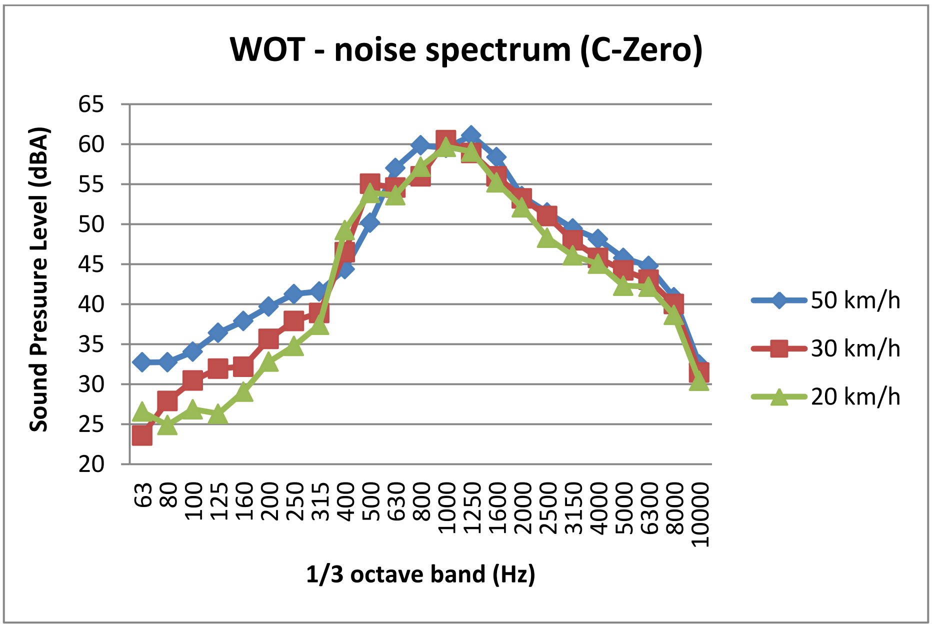
The estimated tyre/road noise and driveline noise are equal between 10-15 km/h ($LpA_{tyre/road}$ = **37.1 log(v) – 3.3**, $LpA_{driveline}$ = **16.0 log(v) + 19.0**). The velocity slope around 200-400 Hz is m = 17 and m = 36 at 800-1250 Hz which are similar to the velocity slope in the total noise analysis.

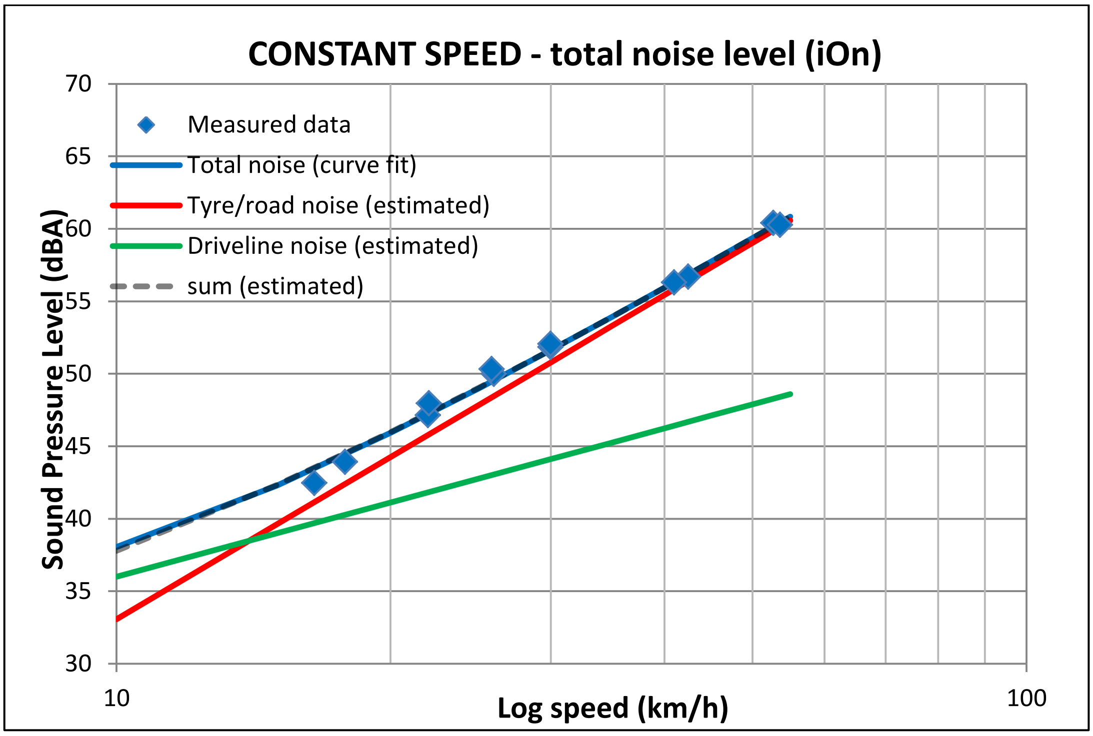


WOT – total noise level (C-Zero)		
Start speed	**Sound Pressure Level**	
50 km/h	67 dBA	68 dBC
30 km/h	66 dBA	67 dBC
20 km/h	65 dBA	66 dBC

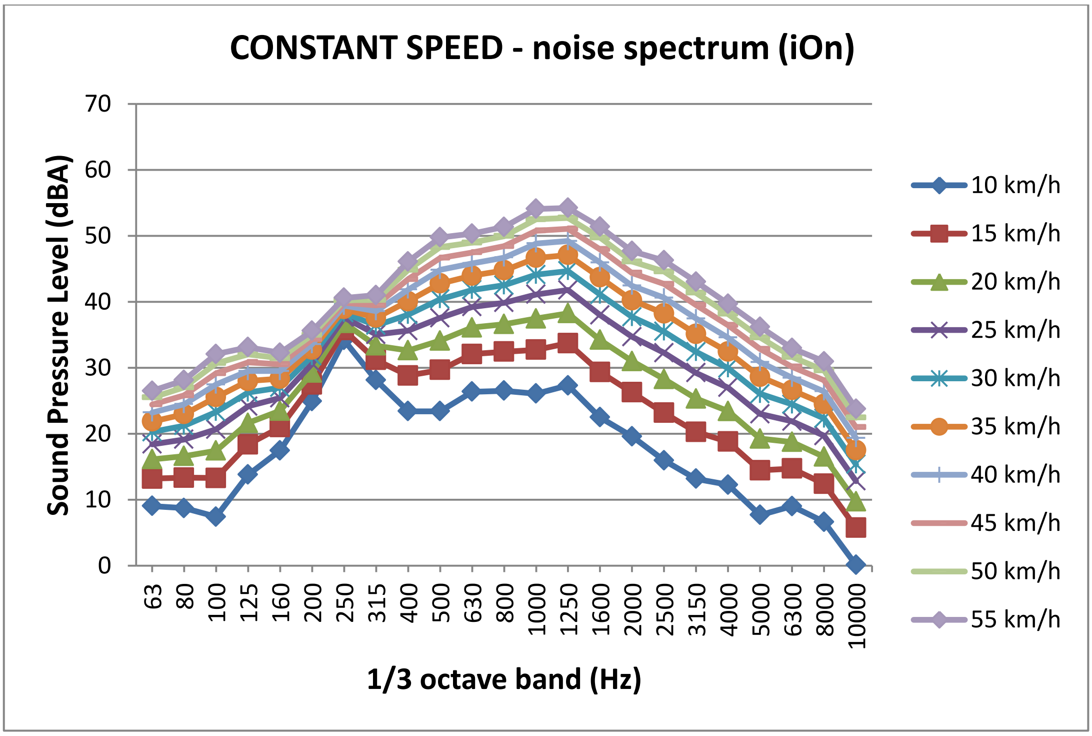


Note that the driveline noise is dominating at start speed 20 and 30 km/h. Note the significant peak around 1000 Hz.

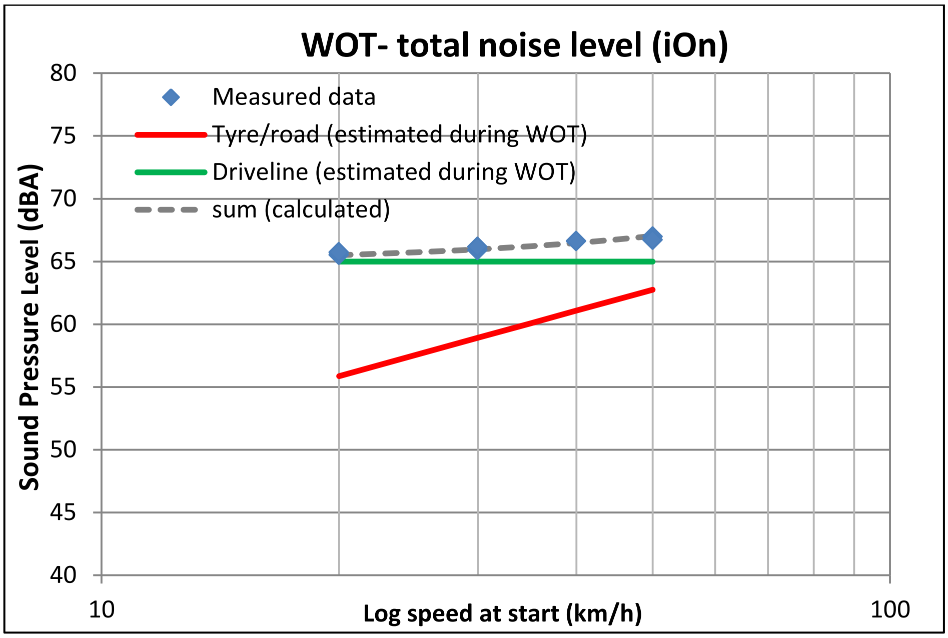




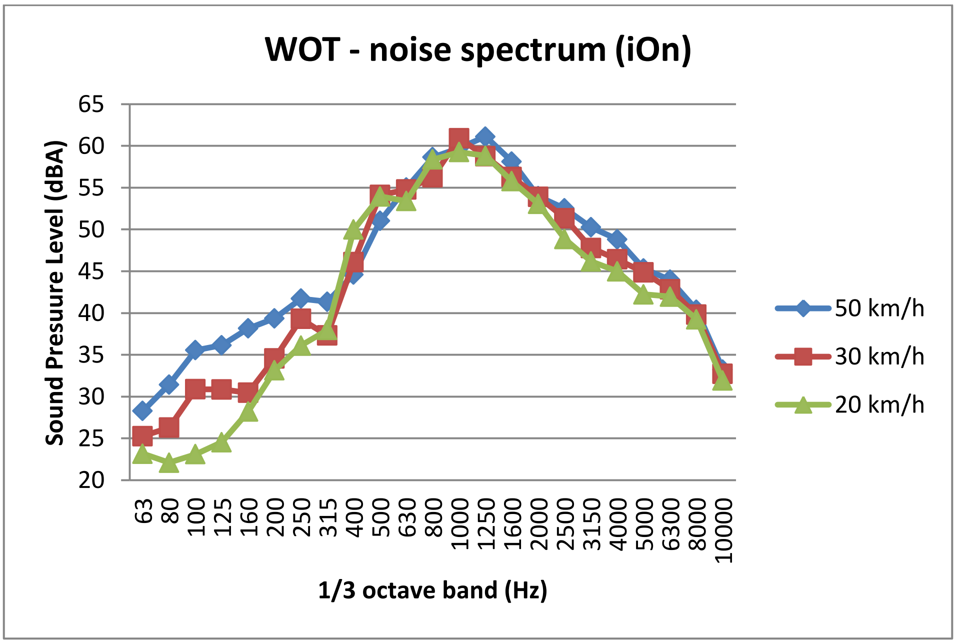
The estimated tyre/road noise and driveline noise are equal between 10-15 km/h ($LpA_{tyre/road}$ = **37.1 log(v) – 4,1**, $LpA_{driveline}$ = **17.0 log(v) + 19.0**). The velocity slope around 200-400 Hz is m = 17 and m = 37 at 800-1600 Hz which are similar to the velocity slope in the total noise analysis. These results are very similar to the previous results for Citroen C-Zero.



WOT – total noise level (iOn)		
Start speed	**Sound Pressure Level**	
50 km/h	67 dBA	68 dBC
30 km/h	66 dBA	67 dBC
20 km/h	66 dBA	66 dBC



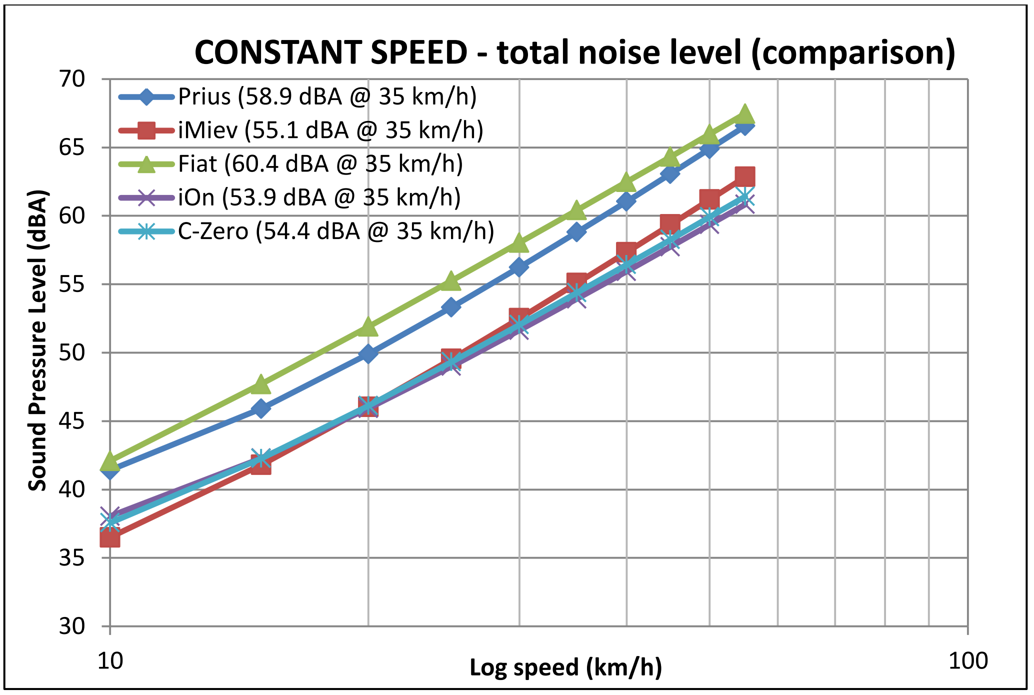
Note that the driveline noise is dominating at all speeds, especially at 20 and 30 km/h. Note the significant peak around 1000 Hz similar to Citroen C-Zero.



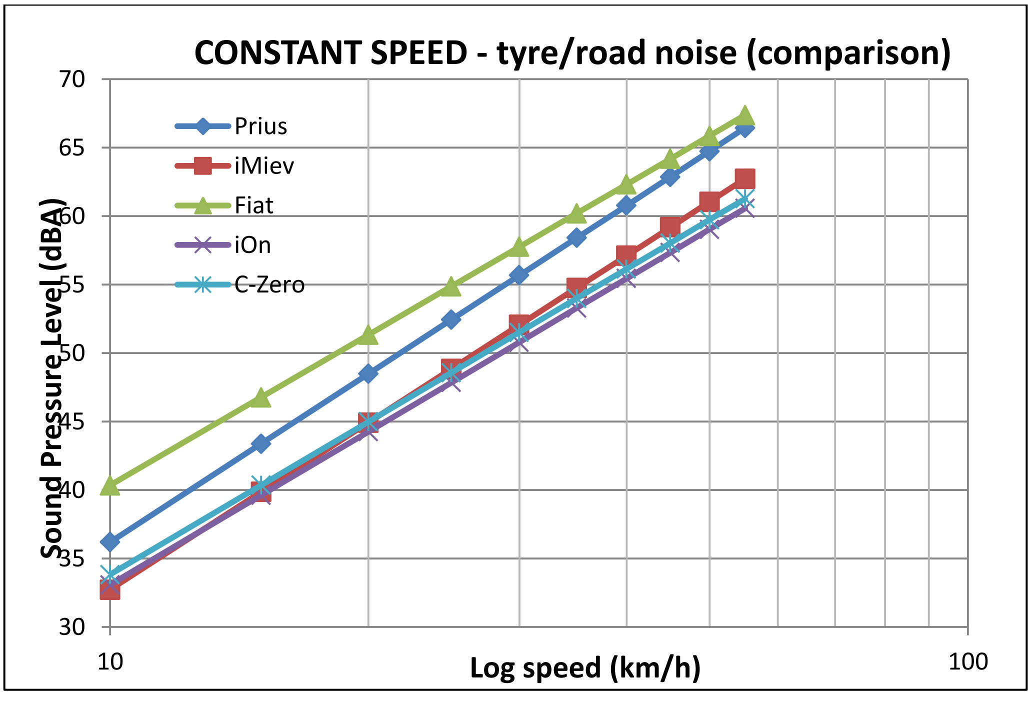
Summary, discussion and comparison of results

Constant speed test

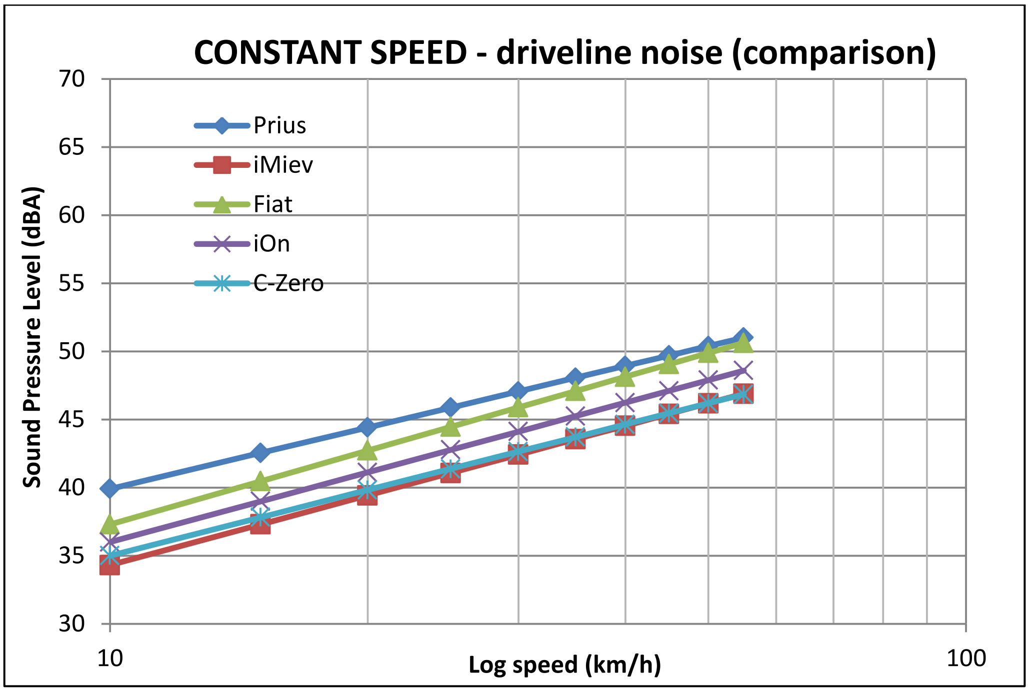
The total noise levels in the diagram below show that iMiev, iOn and C-Zero are the most silent cars, while Prius and Fiat are the noisiest cars. The difference between the highest (Fiat) and the lowest (iOn) total noise is about 6 dBA above 20 km/h.



The estimated tyre/road noise are compared in the diagram below. The difference between the highest (Fiat) and the lowest (iOn) tyre/road noise is about 6 dBA at all vehicle speeds.



The estimated driveline noise are compared in the diagram below. The difference between the highest (Prius) and the lowest (iMiev/C-Zero) driveline noise is about 5 dBA at low speeds.



Note that the driveline noise are assumed to be linear in a logarithmic-speed-diagram which may not be the case, especially not for cars with several gears in the transmission. However, at low speeds and for cars with automatic one gear transmission, it should be a relatively good assumption. It should also be mentioned that a correct estimation of the driveline noise from the A-weighted total noise requires a relatively low tyre/road noise. This is not fullfilled with Fiat, and should therefore serve only as a very rough estimation.

Wide-open-throttle test (wot)

Measurements show that the total noise during wot test at start speed 50 km/h (according to ISO 362:2007) is mostly tyre/road noise. At lower start speeds, the driveline noise is dominating, especially at 20 km/h.

The main idea with the wot test is to simulate a worst-case-scenario with a focus on driveline noise. However, for electric cars the main focus at start speed 50 km/h is on tyre/road noise due to the quite driveline. The noise limits given in the EU Directiv are based on the wot test with start speed 50 km/h. If the noise from a normal combustion engine car are compared to an electric car, we are then comparing engine noise on the normal car with tyre/road noise on the electric car. This does not give a fair picture of the noise reduction potential of electric cars in urban areas. Therefore, we recommend that the wot test for electric cars are to be performed at a lower start speed, e.g. 20 or 30 km/h.

At start speed 20 km/h, Fiat is the most silent car. The total noise from Fiat is about 3-6 dBA lower than the other cars. This is primarily due to lower torque and weaker motor power.

APPENDIX 2

Sound measurements on hybrid and electric vehicles by HAC, June 2011

The exterior noise of electric vehicles is dominated by two noise sources, tyre/road noise and driveline noise. The electric engine, the transmission and the power converter contribute to the driveline noise.

The tyre/road noise of electric vehicles is comparable to the tyre/road noise of conventional vehicles powered by internal combustion engines. The difference is mainly related to the driveline noise. To explore the pass-by noise of electric vehicles in detail, a separation of the acoustical contributions of the main noise sources is necessary. To achieve this separation HAC carried out several measurements of electric vehicles. A simulation tool (a Traffic Noise Synthesizer (TNS) developed in WP 3.1) used the data of the performed acoustical measurements in order to estimate the pass-by noises of the individual sources of the vehicles.

Test vehicles

Vehicle	Electric Engine	Transmission	Tyres
Mitsubishi iMIEV	47 kW	Automatic, 1 speed	Dunlop Enasave Front: 145 / 65R15 Rear: 175 / 55R15
Fiat 500 Liion (Prototype developed by FEV)	30 kW (nominal) 60 kW (peak)	Automatic, 1 speed	Dunlop Duratech 175 / 65R14

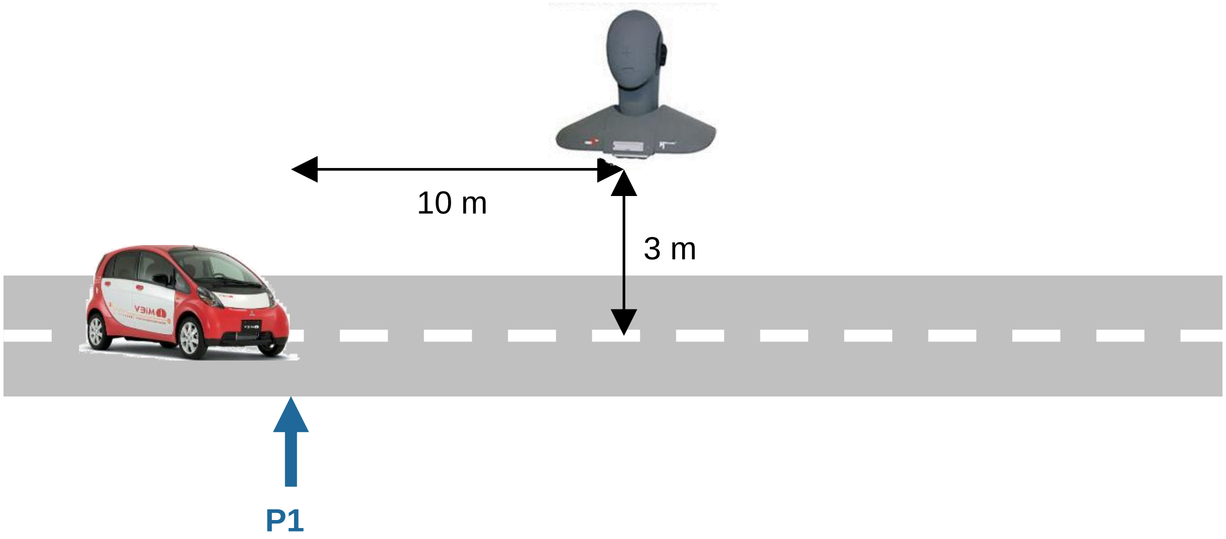
Test Site

The measurements were performed on a small side street in the country near Aachen, Germany. The pictures below illustrate the test environment (left) as well as the smoothness of the road surface (right).

Measurements

Procedure and setup

The measurements were performed in June, 2011. The measurement setup is shown in the figure below.



Diverse measurements were performed in order to consider all relevant driving situations adequately. Several pass-by noise measurements were carried out with respect to constant speed situations (20 km/h, 30 km/h and 50 km/h). Moreover, pass-by scenarios were measured as well, where the vehicle was accelerated at point 1 (P1 in the upper figure). The vehicle approaches at constant speed (20 km/h, 30 km/h and 50 km/h) and at point P1 (10 m distance to the artificial head measurement system) the vehicle accelerates with wide open throttle (WOT). The table below summarizes the considered situations.

Constant speed situations with	Acceleration (WOT) from P1 with starting speed of
20 km/h	20 km/h
30 km/h	30 km/h
50 km/h	50 km/h

The tested vehicles were equipped with near-field microphones at the relevant noise sources. During the test drives the near-field microphone signals were recorded and the exterior noise was measured with an artificial head at 3 m distance to the vehicle at the closest point (see the upper figure).

The following near-field microphone positions were chosen:

- front left tyre inlet
- front left tyre outlet
- inside the engine compartment under the rear trunk
- back side of vehicle (behind the engine compartment)

In addition to the recording of the microphone signals, the velocity and the position of the vehicle were logged during all measurements.

The following figures display the microphone positions for both test vehicles.

iMiEV

Engine compartment (microphone not visible)

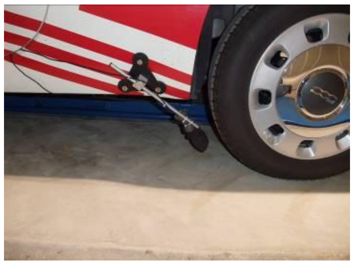
Microphone behind engine compartment

Microphone front left tyre inlet

Fiat 500 Liion

Engine compartment (microphone not visible)

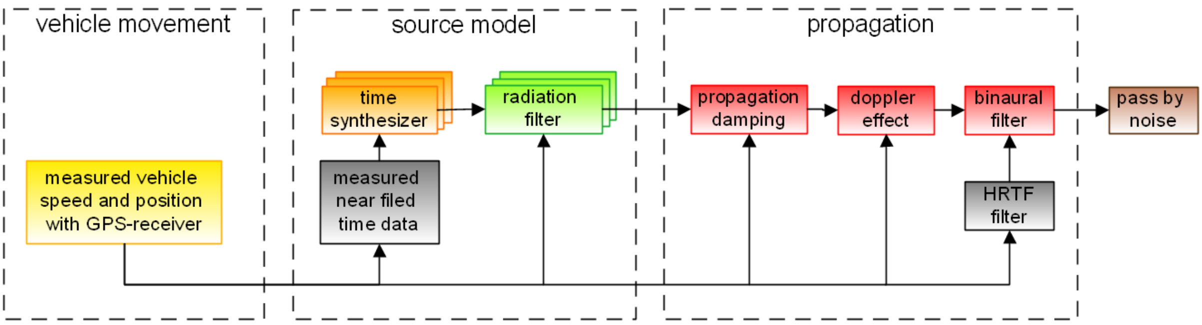
Microphone in front of engine compartment



Microphone front left tyre inlet

Synthesis

HAC is developing a synthesis tool to auralize exterior noise of vehicles as well as to auralize the noise of whole road traffic scenarios. The synthesis of the source signals can be based on different data. In this work task a time signal based synthesis was carried out. In the figure below the signal processing flow of the synthesis within the TNS is shown.



The synthesis is controlled by the position of the vehicle and the speed information during the performed tests. Firstly, the synthesis tool works with the measured near-field signals. Each source (tyre/road and driveline) corresponds to the measured near-field microphone signal. These signals are processed by the simulation software.

To model the radiation characteristics from the near-field to the far-field, the near-field microphone signals are modified using radiation filters. For each source, specific characteristics must be considered.

1. **Driveline:** The driveline noise was recorded with one microphone mounted inside the engine compartment. This is advantageous, because the recorded noise was influenced only slightly by tyre/road noise and crosstalk conflicts are negligible. As the engine compartment and covering damp the radiation of the engine noise, the transfer path through the engine compartment covering must be taken into account. Therefore, another microphone signal, outside the engine compartment, was measuring the engine noise during the test drives as well. From these two microphone signals a transfer function was calculated, representing the radiation (damping) from inside to outside of the engine compartment.
2. **Tyre/road:** The tyre-road noise was recorded close to the contact position between tyre and road surface. Different to the driveline microphones, there is no compartment around the tyres. In a previous EU research project Quiet City Transport HAC did investigations about the radiation effect of tyre noise (horn effect). From these investigations radiation filters resulted, which allow for an estimation of the the tyre/road noise radiation.

The resulting filtered source signals were used to calculate the propagation to the receiver position. The propagation calculation consists of the following steps:

1. Damping of the source signals due to the distance between source and receiver.
2. Damping of the signals due to the air absorption.
3. Frequency shift of the signals due to the relative speed between source and receiver (Doppler Effect).
4. Binaural filtering of the signals depending on the angle of the source in relation to the receiver.

In addition to the aspects considered within the simulation, there are some aspects, which were not taken into account:

1. Angle dependent radiation of the sources
2. Noise differences due to different tyres
3. Speed and direction of wind influencing the propagation
4. The assumption that two sources describe the noise of the entire vehicle is not exact.

The simulation results were validated using the results of measured overall pass-by noise (artificial head recordings).

To adapt the tyre/road noise levels a pass-by measurement at 50 km/h while driving in “N-drive” (coast) was analyzed. This driving situation gives the opportunity to record almost exclusively the tyre/road noise contribution. With this recording a calibration of the source signal was carried out.

The weighting factor of the driveline noise cannot be exactly determined, because of two reasons:

1. It is not possible to drive an electric vehicle, which produces only driveline noise. The best measurement condition is a pass-by at full acceleration.
2. Because the tyre/road noise contribution dominates in the far-field the weighting factor for the driveline noise contribution can be determined only with limited accuracy. In particular, the driveline noise levels of the Fiat 500 Liion are clearly below the tyre/road noise levels.

Another aspect is that the near-field microphones include partially crosstalk from other sources (e.g., the driveline microphone records also tyre/road noise). This leads to small uncertainties with respect to the separation of the sources in the synthesis model.

An advantage of the synthesis method is that the background noise does not influence the measurement results, because the near-field microphones are very close to the sources.

With a valid synthesis model, the contribution of each noise source or the total noise can be auralized binaurally or monaurally for any receiver position. For the analysis, the far-field pass-by signals were calculated for a monaural microphone at a distance of 7.5 m to the track.

Analysis

The evaluation of the pass-by sound pressure levels was done from two points of view. On the one hand, the near-field signals are interpreted and on the other hand, the simulated far-field signals are evaluated.

From the near-field microphone signals we can extract the exact sound pressure levels of the individual sources during the measurements. Two aspects have to be considered.

1. Crosstalk between the source microphones must be negligible. In case of the tyre/road microphones this is clearly achieved. The driveline near-field microphone includes partially tyre/road noise. This should be considered in the evaluation of the results.
2. The near-field sound pressure levels include no information about the sound pressure level at the receiver position. The near-field levels can only be used to evaluate the relative differences from one driving condition to another driving condition for each vehicle and each noise source.

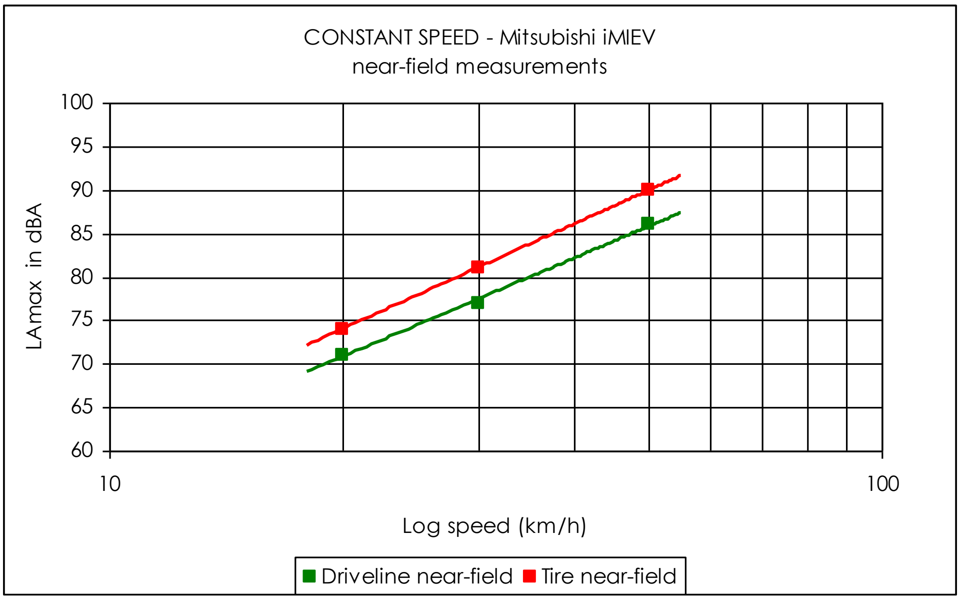
The sound pressure levels derived from the simulated far-field signals allow for an estimation of the contribution of the driveline and the tyre/road noise to the overall pass-by noise.

The following figures display the maximum A-weighted sound pressure levels (L_{Amax}) during the different pass-by scenarios (measurements and simulations).

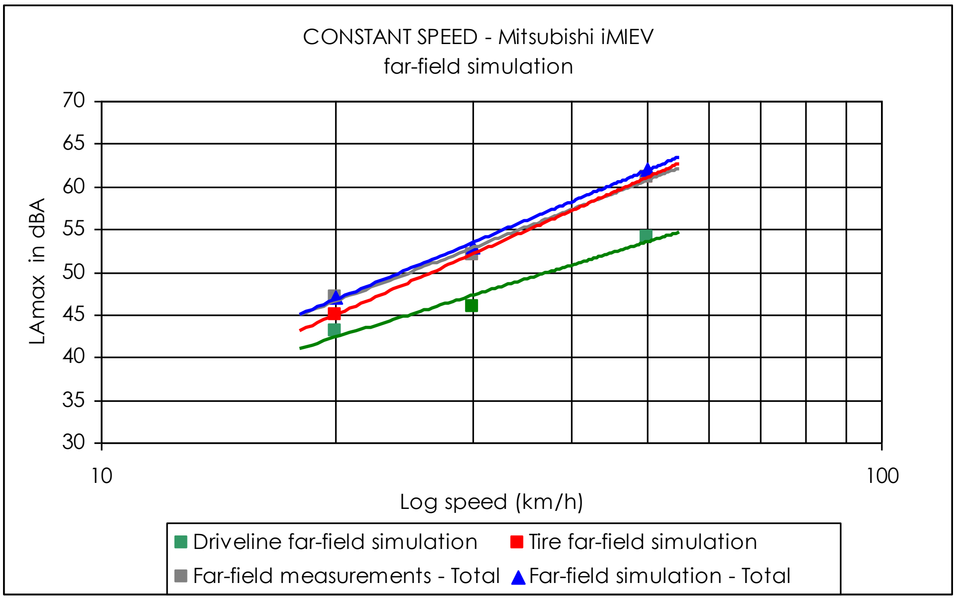
Mitsubishi iMiEV

Constant speed situation

The sound pressure levels of the tyre/road noise and of the driveline noise increase with increasing speed. In the far-field the noise of both sources increases from 20 km/h to 50 km/h by 11 to 16 dB. The tyre/road noise levels are 2 to 7 dB higher than the driveline sound pressure levels in general. The difference between the tyre/road noise and of the driveline noise contribution increases with increasing speed.



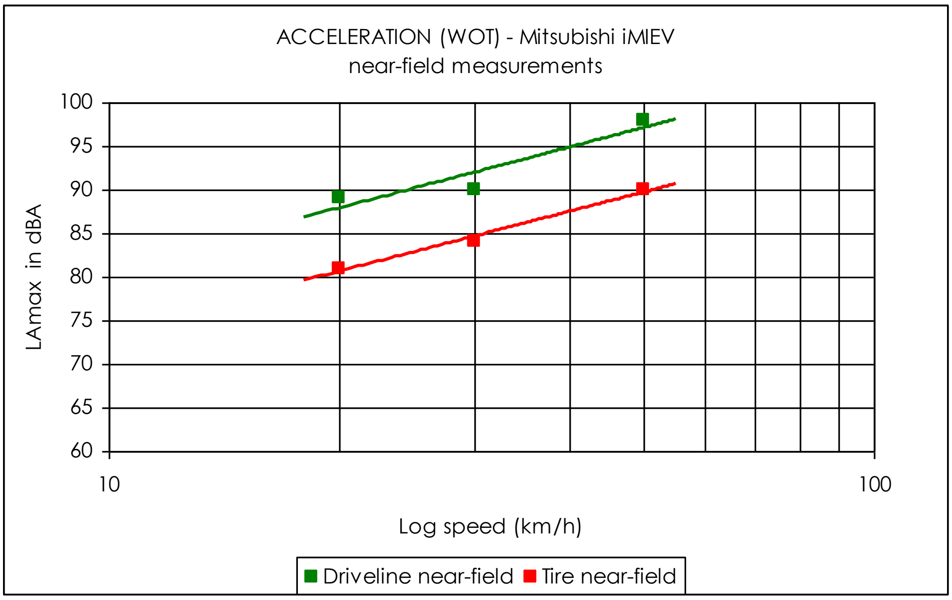
Sound pressure levels (L_{Amax}) of the near-field microphones for the driving condition "constant speed" (20 km/h, 30 km/h, 50 km/h).



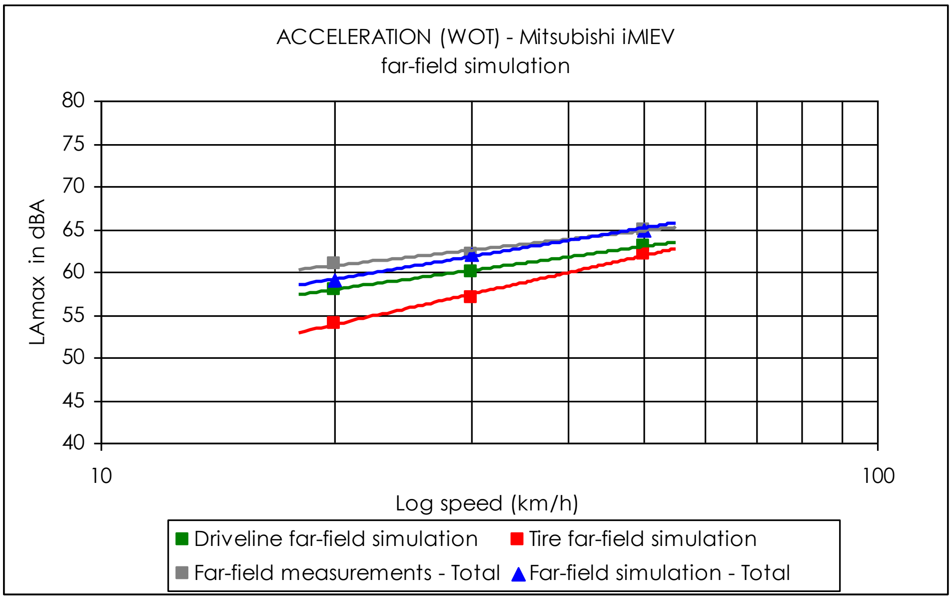
Pass-by sound pressure levels (L_{Amax}) at the far-field position (7.5 m) for the driving condition "constant speed" (20 km/h, 30 km/h, 50 km/h). The determination of the total sound pressure levels and the contributions of each source are based on a simulation. In addition, the measured total sound pressure levels are plotted.

Driving condition: Acceleration (WOT)

The sound pressure levels of the tyre/road noise and of the driveline noise increase with increasing speeds for the driving condition “full acceleration (WOT)”. The noise of the sources increases from 20 km/h to 50 km/h by 5 dB (driveline) and 8 dB (tyre/road) in the far-field. The driveline noise dominates the overall pass-by noise in the far-field, in particular for the lower starting speed situations (20 km/h and 30 km/h).



Sound pressure levels (L_{Amax}) of the near-field microphone for the driving condition “full acceleration (WOT)” starting at different speeds (20 km/h, 30 km/h, 50 km/h).



Pass-by sound pressure levels (L_{Amax}) at the far-field position (7.5 m) for the driving condition “full acceleration (WOT)” starting at different speeds (20 km/h, 30 km/h, 50 km/h). The determination of the total sound pressure levels and the contributions of each source are based on a simulation. In addition, the measured total sound pressure levels are plotted.

FIAT 500 LIION

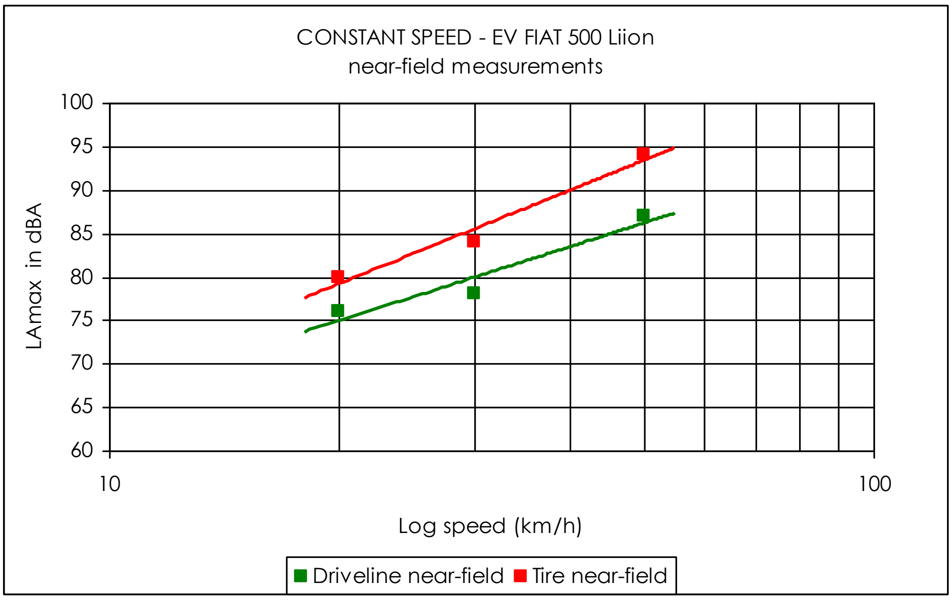
In comparison to the Mitsubishi iMIEV the driveline noise contribution of the Fiat 500 Liion is lower, whereas the overall sound pressure levels are similar. The contribution of the tyre/road noise source are slightly higher for the the Fiat 500 Liion compared to Mitsubishi iMIEV.

As explained earlier the lower driveline sound presssure levels allows for only an estimation with a higher uncertainty. Taking into account this fact, the sound pressure levels of the driveline noise must be interpreted carefully.

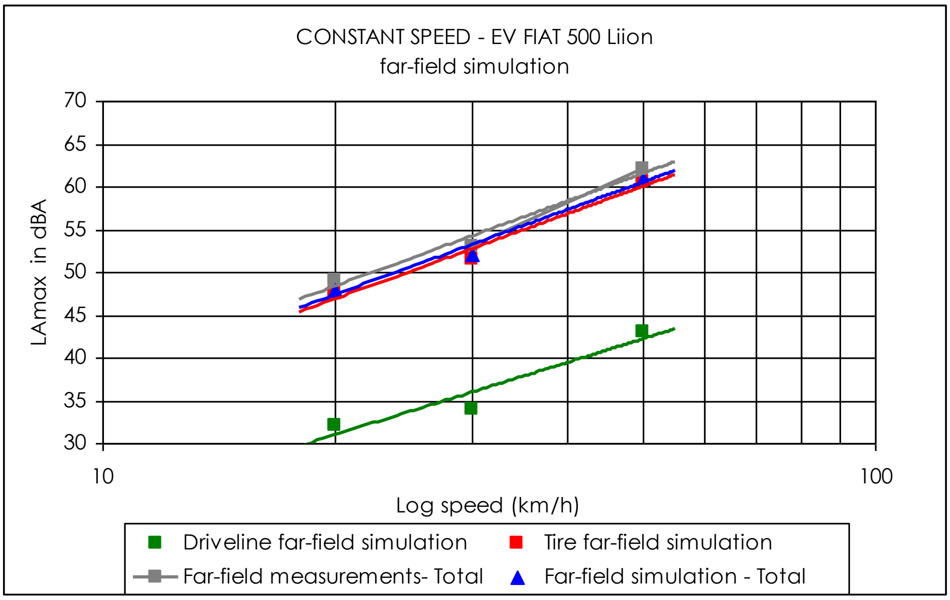
Constant speed situation

The sound pressure level of the tyre/road noise and of the driveline noise increases with increasing speed. In the far-field the noise of the sources increases from 20 km/h to 50 km/h by 11 dB (driveline) and 14 dB (tyre/road).

The tyre/road noise contribution is dominant in all measurements. Considering the far-field the contribution of the tyre/road noise is around 16 dB higher than the noise contribution of the driveline.



Sound pressure levels (L_{Amax}) of the near-field microphones for the driving condition "constant speed" (20 km/h, 30 km/h, 50 km/h).

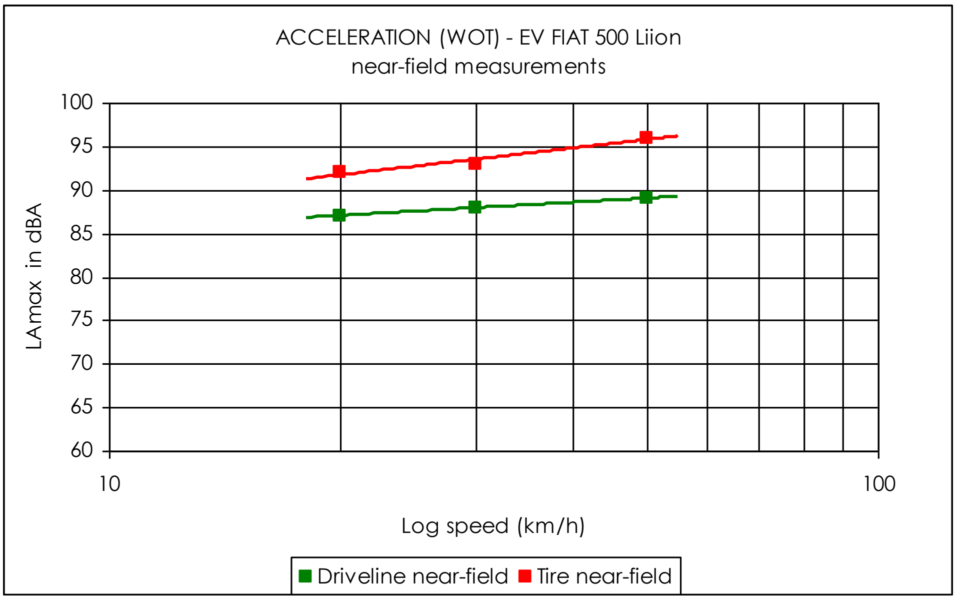


Pass-by sound pressure levels (L_{Amax}) at the far-field position (7.5 m) for the driving condition "constant speed" (20 km/h, 30 km/h, 50 km/h). The determination of the total sound pressure levels and the contributions of each source are based on a simulation. In addition, the measured overall noise levels are plotted.

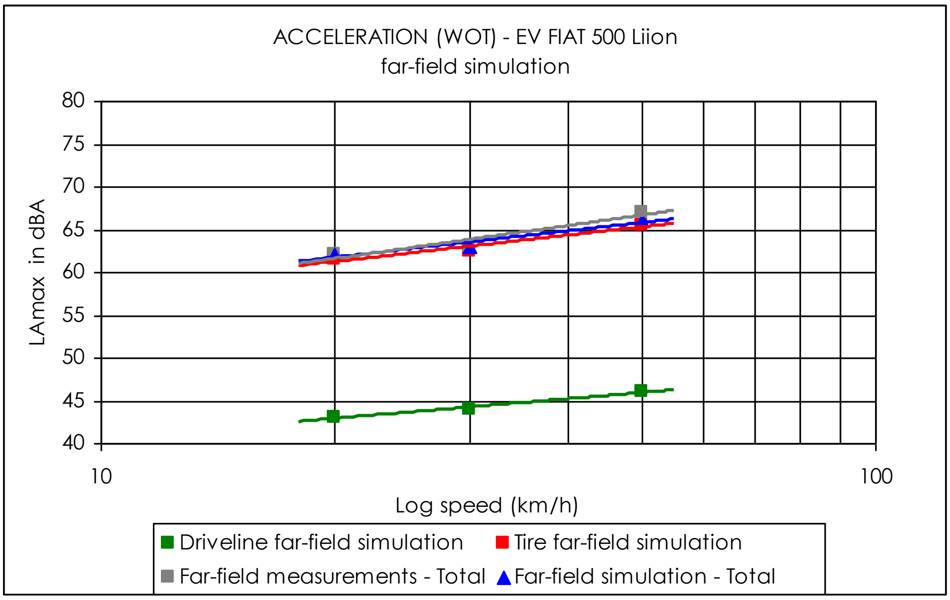
Driving condition: Acceleration (WOT)

The sound pressure level of the tyre/road noise and of the driveline noise increases only slightly with increasing speed for the driving condition "full acceleration (WOT)". In the far-field the noise of both sources increases from 20 km/h to 50 km/h by approximately 3 dB.

The tyre/road noise contribution is dominant in all measurements. In the far-field the tyre/road sound pressure levels are around 18 dB higher than the driveline sound pressure levels.



Sound pressure levels (L_{Amax}) of the near-field microphone for the driving condition "full acceleration (WOT)" starting at different speeds (20 km/h, 30 km/h, 50 km/h).



Pass-by sound pressure levels (L_{Amax}) at the far-field position (7.5 m) for the driving condition "full acceleration (WOT)" starting at different speeds (20 km/h, 30 km/h, 50 km/h). The determination of the total sound pressure levels and the contributions of each source are based on a simulation. In addition, the measured total sound pressure levels are plotted.

CONCLUSIONS

The measurements and simulations of the Mitsubishi iMIEV show that with respect to the driving condition “constant speed” the tyre/road sound pressure levels are higher than the driveline sound pressure levels. The difference between the tyre/road noise and driveline noise contribution increases with increasing speed. This conclusion is confirmed by measurements and estimations performed by ACL.

Considering the driving condition “full acceleration (WOT)” the dominant noise source of the Mitsubishi iMIEV is the driveline. The different analyses show that the driveline sound pressure levels are higher than the tyre/road sound pressure levels. This difference decreases with increasing (starting) speed. At a starting speed of 50 km/h the sound pressure levels of the tyre/road and driveline are nearly equal. The same relationship between the tyre/road and driveline noise contribution was found by ACL.

The driveline sound pressure levels of the Fiat 500 Liion are much lower than the driveline sound pressure levels of the investigated Mitsubishi iMIEV. This leads to a dominance of the tyre/road noise contribution in all driving conditions (constant speed and acceleration (WOT)). This means that this electric vehicle would greatly benefit from low noise tyres.

The results from ACL are comparable to the HAC simulation results presented in this Appendix 2. Only minor differences can be found. However, it has to be mentioned that the EV Fiat used during tests performed by ACL and the Fiat 500 Liion measured by HAC are not identical, but rather even different prototypes with different engines. This means that only the tyre/road noise contribution is comparable.

The low sound pressure levels of the driveline noise, especially regarding the driving condition constant speed, causes difficulties with respect to the estimations. As the tyre/road noise estimations differ only slightly from the measured total noise (less than 1 dB regarding the driving condition constant speed), the driveline noise contribution to the total noise is almost negligible. Calculating the driveline noise by subtracting the estimated tyre/road noise contribution from the total noise means that even a small uncertainty in the tyre/road sound pressure level estimation results in a great uncertainty of the estimated driveline sound pressure levels.

In contrast to the results from ACL, the performed simulations show a slight increase of the driveline noise contribution with increasing speed by approximately 3 dB for the driving conditions with acceleration. This determined tendency is supported by the measured near-field driveline signals. For all considered driving conditions it was found that with a higher speed the contribution of driveline in the near-field increases. Thus, the far-field estimation of the driveline noise contribution is plausible. However, this small deviation does not effect at all the general conclusions drawn by ACL and HAC with respect to the adequate testing of electric vehicles focusing on Q-zones.

HAC confirmed that for full acceleration at lower starting speeds the driveline noise contribution is very important. Since the WOT driving situation is intended to reflect a worst case scenario with the focus on driveline noise, the consideration of a WOT situation with a lower starting speed than 50 km/h for testing and approving electric vehicles appears imperative. This finding supports the conclusions drawn by ACL. This means that the measurement protocol for electric vehicles must contain a WOT acceleration with a starting speed of 20 or 30 km/h.