METHODS OF ANALYSIS AND EVALUATION OF ELECTROMAGNETIC RADIATION DURING TESTS OF ELECTROMAGNETIC COMPATIBILITY (EMC) OF MOTOR VEHICLES, IN PARTICULAR ELECTRICALLY DRIVEN

METODY ANALIZY I OCENY PROMIENIOWANIA ELEKTROMAGNETYCZNEGO W BADANIACH KOMPATYBILNOŚCI ELEKTROMAGNETYCZNEJ (EMC) POJAZDÓW SAMOCHODOWYCH ZWŁASZCZA ELEKTRYCZNYCH

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Part II
Analysis of the electromagnetic radiation of selected electric vehicles (EV)

Część II
Analiza promieniowania elektromagnetycznego wybranych pojazdów elektrycznych – EV

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Summary

The article discusses electromagnetic compatibility (EMC) requirements for motor vehicles and their equipment and electromagnetic radiation (EMR) testing methods based on the normative documents that provide grounds for approving specific vehicle types for production and operation (type approval). The normative documents are UN ECE Regulation No 10 and Directive 72/245/EEC. Three groups of methods (line methods, area-related methods, and parameter estimation methods) have been proposed and described for the EMR assessment of vehicles. Based on the EMR tests carried out at PIMOT on a few electric vehicles (EV), the EMR of the vehicles was analysed and assessed with using some of the said methods. The following vehicles were used for the analyses and calculations: OPEL Ampera, RENAULT Fluence, CITROEN C-Zero, and MEGA e-City. The analysis and calculations carried out have revealed a close similarity between the usability of the proposed methods of EMR assessment of motor vehicles. The qualitative optimization of the parameters that can influence the assessment, primarily a reduction in the electromagnetic radiation (EMR) of the vehicle under consideration, will not only result in correct functioning of the vehicle, especially if it is electrically driven, but also will help to avoid possible harmful impact of EMR on vehicle occupants' health. The work outputs may be utilized and disseminated, especially by the designers and researchers who are involved in work on motor vehicles, in particular EVs, where lots of electronic systems and modules are present.

Keywords: electric vehicle (EV) testing, electromagnetic compatibility (EMC) of motor vehicles, analysis of EMC tests, electromagnetic radiation (EMR) of vehicles

Streszczenie

W artykule zostały omówione wymagania kompatybilności elektromagnetycznej (EMC) dla pojazdów i urządzeń samochodowych oraz metody badań promieniowania elektromagnetycznego (PEM) w oparciu o dokumenty normatywne stanowiące podstawę dopuszczenia do produkcji i ruchu (homologacja) danego pojazdu. Dokumentami tymi są Regulamin nr 10 EKG ONZ oraz Dyrektywa 72/245/EWG. Dla oceny PEM pojazdów zostały zaproponowane i opisane trzy grupy metod: liniowe, polowe i estymacji parametrów. Na podstawie przeprowadzonych w PIMOT badań kilku samochodów elektrycznych w zakresie PEM przeprowadzono analizę i ocenę wg wybranych metod. Do analizy i obliczeń wykorzystano następujące pojazdy: OPEL Ampera, RENAULT Fluence, CITROEN C-Zero i MEGA e-City. Przeprowadzona analiza i obliczenia wykazały dużą zbieżność przydatności zaproponowanych metod oceny PEM pojazdów samochodowych. Zapewnienie wysokich jakościowo parametrów wpływających na ocenę, w tym przede wszystkim promieniowania elektromagnetycznego (PEM) ma wpływ nie tylko na poprawne działanie pojazdu, szczególnie EV, ale też na zdrowie przebywających wewnątrz: kierowcy i pasażerów. Wyniki pracy mogą być wykorzystane i rozpowszechniane szczególnie przez konstruktorów i badaczy pojazdów samochodowych, zwłaszcza EV, w których występują duże ilości systemów i modułów elektronicznych.

Słowa kluczowe: badania pojazdów elektrycznych (EV), EMC pojazdów samochodowych, analiza badań EMC, promieniowanie elektromagnetyczne pojazdów

1. Analysis and assessment of the EMR of selected electric vehicles (EV)

To verify the practical usability of the methods of analysis and assessment of the EMR of electric vehicles as proposed in Section 4 of part I of this article, four electric vehicles were tested at the PIMOT Electronics and Acoustics Laboratory; afterwards, necessary calculations were carried out and their results have been presented below. The test and assessment specimens were the following mass-produced electric vehicles:

- OPEL Ampera;
- RENAULT Fluence;
- CITROEN C-Zero;
- MEGA e-City.

The vehicles were selected in consideration of their market availability.

Technical specifications of the vehicles under test (VUT) have been given in Table 1 and their general view has been shown in Figs 1, 2, 3, and 4.

The EMR of these vehicles was analysed and assessed with using the following methods from among those specified in Section 4 of part I of this article:

- two-line-plus method (ML2+);
- two-line area-related method (MP2);
- parameter estimation method (MEP).

Table 1. Basic technical specifications of the EV under test (manufacturers' catalogue data)

Parameter	**OPEL Ampera**	**RENAULT Fluence**	**CITROEN C-Zero**	**MEGA e-City**
Body type	sedan	sedan	hatchback	passenger-cargo
– doors	5	4	5	3
– seats	4	5	4	2
Curb mass [kg]	1 715	1 605	1 110	750
Gross vehicle mass [kg]	2 080	2 035	1 450	1 055
Luggage capacity [dm3]	300	315	256	900
Electric motor	AC	AC	AC	DC
– power output, continuous [kW]	111	70	49	8
– rated voltage [V]	950	400	330	48
Traction battery				
– capacity [kWh]	16	22	16	about 10
– type	lithium-ion	lithium-ion	lithium-ion	lithium-ion
Maximum speed [km/h]	161	135	130	64
Acceleration 0-100 km/h [s]	9	13	15.9	not available

Table 1. Basic technical specifications of the EV under test (manufacturers' catalogue data), cont.

Parameter	**OPEL Ampera**	**RENAULT Fluence**	**CITROEN C-Zero**	**MEGA e-City**
Range [km]	56*	185	150	65
Body dimensions:				
– length [cm]	441	462	348	296
– width [cm]	180	181	148	143
– height [cm]	143	148	161	147

* About 500 km for the HEV version (with a hybrid drive system)

Fig. 1. OPEL Ampera [22]

Fig. 2. RENAULT Fluence [22]

Fig. 3. CITROEN C-Zero [22]

Fig. 4. MEGA e-City [22]

2. EMR assessment by the two-line-plus method (ML2+)

The electromagnetic emission from the vehicles was measured in the conditions of an open area test site, in accordance with UN ECE Regulation No 10.04 and CISPR 12 requirements. The measurements were carried out twice for each of the VUTs: for the vehicle and background emissions taken together and for the background radiation only. The numerical data obtained from the measurements were used as input data for a further analysis. Within the tests, an attempt was also made to eliminate the background radiation level by mathematical operations on the data obtained from measurements of the vehicle and background emissions taken together and the background radiation taken alone.

The electromagnetic emission measurement results obtained for individual vehicles have been presented in Figs 5–12, for two frequency subranges, i.e. 30-300 MHz and 300–1 000 MHz.

To eliminate the background electromagnetic emission by computational subtraction of the background signal from the total vehicle and background signal, mathematical transformations were carried out with using the following relations:

$$X\left[\frac{\mathrm{V}}{\mathrm{m}}\right] = 10^{\frac{X\left[\frac{\mathrm{dB\mu V}}{\mathrm{m}}\right]-120}{20}} \tag{1}$$

$$P\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] = \frac{\left(X\left[\frac{\mathrm{V}}{\mathrm{m}}\right]\right)^2}{377} \tag{2}$$

$$X\left[\frac{V}{m}\right] = \sqrt{P\left[\frac{W}{m^2}\right]\cdot 377} \tag{3}$$

$$X\left[\frac{dB\mu V}{m}\right] = 20\cdot\log X\left[\frac{V}{m}\right] + 120 \tag{4}$$

Assuming:

$X_2\left[\frac{\mathrm{dB\mu V}}{\mathrm{m}}\right]$ as the total vehicle and background electromagnetic emission level and

$X_1\left[\frac{\mathrm{dB\mu V}}{\mathrm{m}}\right]$ as the bare background electromagnetic emission level

and using equations (1)-(4), we obtain the following formula:

$$\begin{cases} \Delta X\left[\frac{\mathrm{dB\mu V}}{\mathrm{m}}\right] = 10\cdot\log\left(10^{\frac{X_2}{10}} - 10^{\frac{X_1}{10}}\right) & \text{for } X_2 > X_1 \\ 0 & \text{for } X_2 \le X_1 \end{cases} \tag{5}$$

where ΔX is the vehicle emission level to be found with the background emission having been eliminated.

It was found necessary to consider the case with $X_2 \le X_1$ because the background electromagnetic emission signal was non-stationary and the two background emission measurements were not carried out at the same time. This was also the reason for the necessity to verify the result obtained and to remove "manually" the remnant values of the background electromagnetic emission that had not been eliminated by mathematical calculations.

In the subsequent part of this work, a dedicated computer program was used to calculate the width Δf of the band of exceedances of the L_2 (or $\mathrm{L}_{2\mathrm{A}}$) reference level. The reference level was assumed as:

1) (L – 10 dB) for the antenna-VUT distance of 3 m (level L_2) and
2) (L – 8 dB) for the antenna-VUT distance of 10 m (level $\mathrm{L}_{2\mathrm{A}}$),

where L is the limit level defined in UN ECE Regulation No 10.04.

The calculation results for individual vehicles have been presented in Tables 2-5.

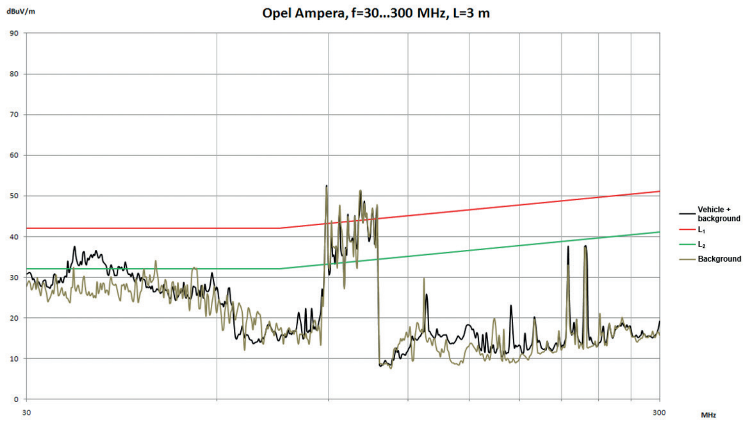


Fig. 5. Vehicle and background electromagnetic emissions: OPEL Ampera, f = 30–300 MHz:
x-axis – frequency [MHz]
y-axis – electromagnetic radiation (EMR) [dBμV/m]

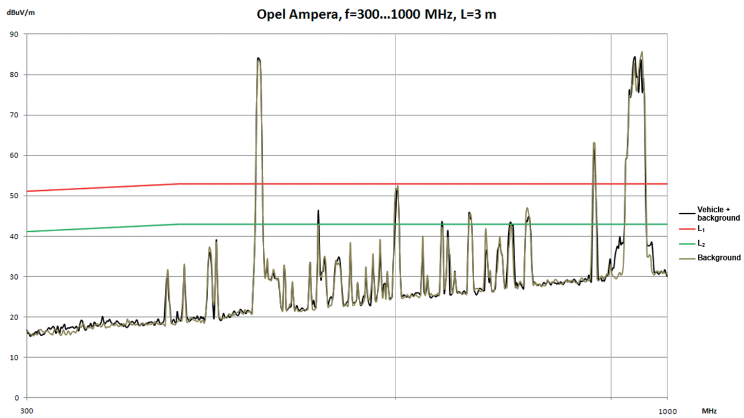


Fig. 6. Vehicle and background electromagnetic emissions: OPEL Ampera, f = 300–1000 MHz:
x-axis – frequency [MHz]
y-axis – electromagnetic radiation (EMR) [dBμV/m]

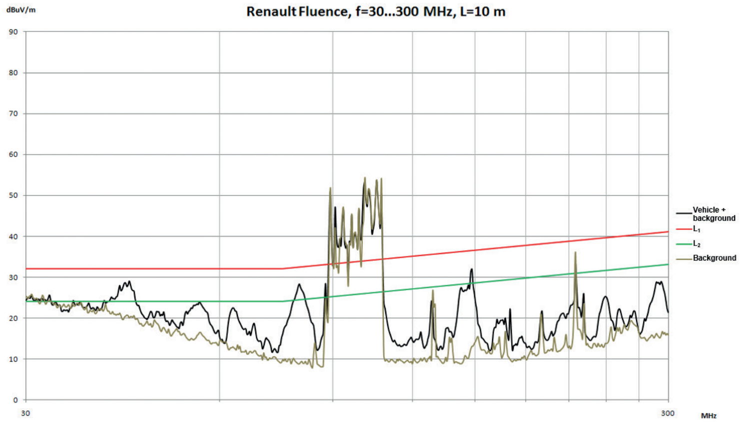


Fig. 7. Vehicle and background electromagnetic emissions: RENAULT Fluence, f = 30–300 MHz:
x-axis – frequency [MHz]
y-axis – electromagnetic radiation (EMR) [dBμV/m]

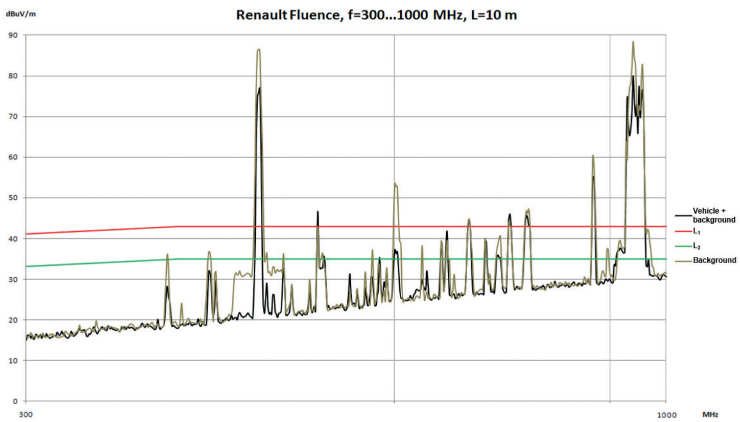


Fig. 8. Vehicle and background electromagnetic emissions: RENAULT Fluence, f = 300–1000 MHz:
x-axis – frequency [MHz]
y-axis – electromagnetic radiation (EMR) [dBμV/m]

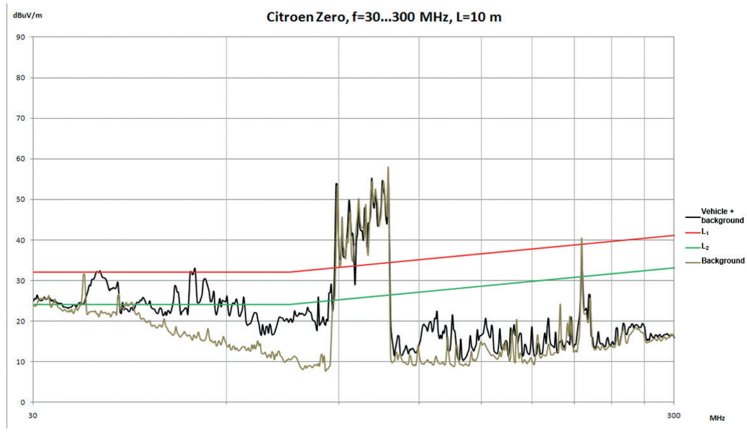


Fig. 9. Vehicle and background electromagnetic emissions: CITROEN C-Zero, f = 30–300 MHz:
x-axis – frequency [MHz]
y-axis – electromagnetic radiation (EMR) [dBμV/m]

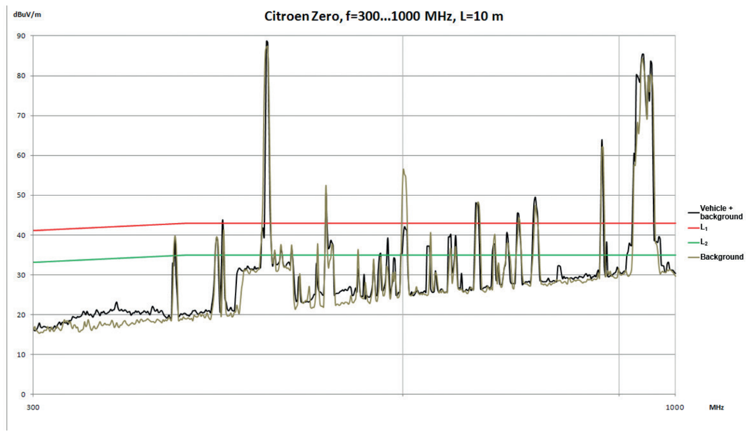


Fig. 10. Vehicle and background electromagnetic emissions: CITROEN C-Zero, f = 300–1000 MHz:
x-axis – frequency [MHz]
y-axis – electromagnetic radiation (EMR) [dBμV/m]

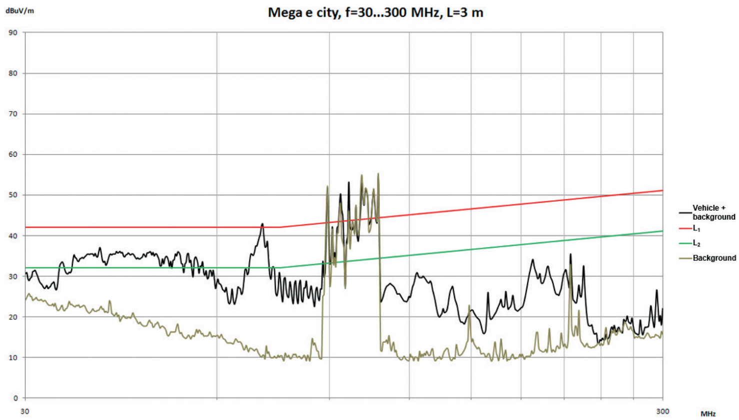


Fig. 11. Vehicle and background electromagnetic emissions: MEGA e-City, f = 30–300 MHz:
x-axis – frequency [MHz]
y-axis – electromagnetic radiation (EMR) [dBμV/m]

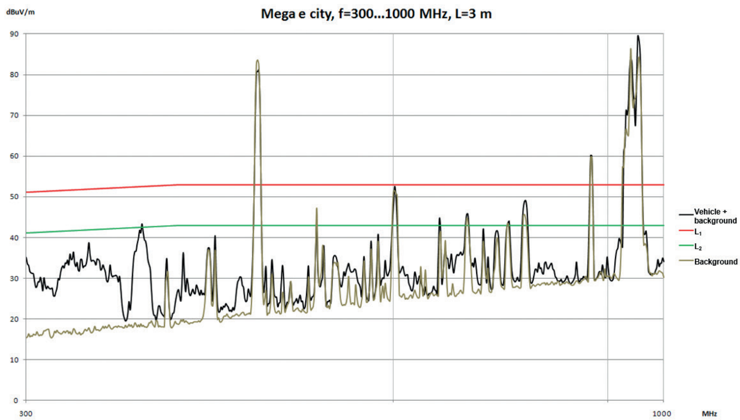


Fig. 12. Vehicle and background electromagnetic emissions: MEGA e-City, f = 300–1000 MHz:
x-axis – frequency [MHz]
y-axis – electromagnetic radiation (EMR) [dBμV/m]

Table 2. Width of the band of exceedances of the values of the L_2 reference (limit) line: OPEL Ampera

OPEL Ampera, L = 3 m f = 30-300 MHz Exceedances of limit line L_2:				
f start [MHz]	**f end [MHz]**	**Δf [MHz]**	**f(Pmax) [MHz]**	**ΔPmax [dBμV/m]**
34.8286	34.8286	0.0000	34.8286	1.3908
35.4277	36.0372	0.6095	35.7312	5.0628
36.5011	39.5814	3.0803	38.5816	4.2284
39.9204	39.9204	0.0000	39.9204	0.1698
42.9217	42.9217	0.0000	42.9217	0.6611
f = 300-1 000 MHz Exceedances of limit line L_2:				
f start [MHz]	**f end [MHz]**	**Δf [MHz]**	**f(Pmax) [MHz]**	**ΔPmax [dBμV/m]**
–	–	–	–	–

Table 3. Width of the band of exceedances of the values of the L_{2A} reference (limit) line: RENAULT Fluence

RENAULT Fluence, L = 10 m f = 30-300 MHz Exceedances of limit line L_{2A}:				
f start [MHz]	**f end [MHz]**	**Δf [MHz]**	**f(Pmax) [MHz]**	**ΔPmax [dBμV/m]**
41.8375	44.2221	2.3846	43.4743	4.5005
78.6393	81.3682	2.7289	79.9921	3.8663
147.8134	148.4450	0.6316	148.4450	3.4448
f = 300-1 000 MHz Exceedances of limit line L_{2A}:				
f start [MHz]	**f end [MHz]**	**Δf [MHz]**	**f(Pmax) [MHz]**	**ΔPmax [dBμV/m]**
–	–	–	–	–

Table 4. Width of the band of exceedances of the values of the L_{2A} reference (limit) line: CITROEN Zero

CITROEN Zero, L = 10 m f = 30-300 MHz Exceedances of limit line L_{2A}:				
f start [MHz]	**f end [MHz]**	**Δf [MHz]**	**f(Pmax) [MHz]**	**ΔPmax [dBμV/m]**
36.3458	40.6072	4.2614	38.0912	8.0497
44.4111	44.4111	0.0000	44.4111	0.2827
49.6181	50.4716	0.8535	49.8301	4.4715

52.4462	53.8053	1.3591	53.5763	8.9586
54.4980	57.3592	2.8612	55.4355	6.3572
58.5952	58.5952	0.0000	58.5952	1.2411
59.0970	60.1137	1.0167	60.1137	1.9667
61.4090	61.4090	0.0000	61.4090	0.1322
61.9350	62.1996	0.2646	62.1996	1.2120
63.8115	63.8115	0.0000	63.8115	1.7154
83.4768	83.4768	0.0000	83.4768	1.1734
86.7426	87.1133	0.3707	87.1133	2.0192
f = 300-1 000 MHz Exceedances of limit line L_{2A}:				
f start [MHz]	**f end [MHz]**	**Δf [MHz]**	**f(Pmax) [MHz]**	**ΔPmax [dBμV/m]**
878.6966	878.6966	0.0000	878.6966	2.5892

Table 5. Width of the band of exceedances of the values of the L_2 reference (limit) line: MEGA e-City

MEGA e-City, L = 10 m f = 30-300 MHz Exceedances of limit line L_2:				
f start [MHz]	**f end [MHz]**	**Δf [MHz]**	**f(Pmax) [MHz]**	**ΔPmax [dBμV/m]**
33.9488	34.3859	0.4371	34.2396	1.1815
35.5791	50.6873	15.1082	39.2453	4.9537
51.1214	52.8954	1.7740	52.0008	3.9266
53.3484	54.4980	1.1496	54.0352	3.5921
55.1996	55.9103	0.7107	55.4355	2.7252
56.3891	56.8721	0.4830	56.8721	1.4921
67.4486	72.2109	4.7623	70.6876	10.9299
73.1406	73.4531	0.3125	73.4531	0.3262
f = 300-1 000 MHz Exceedances of limit line L_2:				
f start [MHz]	**f end [MHz]**	**Δf [MHz]**	**f(Pmax) [MHz]**	**ΔPmax [dBμV/m]**
373.2622	373.2622	0.0000	373.2622	0.8607

At the last stage of this work, the coefficient of excessive electromagnetic emission (representing the exceedances of the L_2 or L_{2A} reference levels) was determined from the data on the frequency ranges where the exceedances were recorded.

This coefficient is expressed by a formula:

$$k = \frac{\Delta f}{F} \cdot 100\% \tag{6}$$

where F = 970 MHz for tests carried out in the frequency range 30-1 000 MHz.

The values of this coefficient for individual vehicles were calculated with using a dedicated computer program. The calculation results have been presented in Table 6 and illustrated by a graph in Fig. 13.

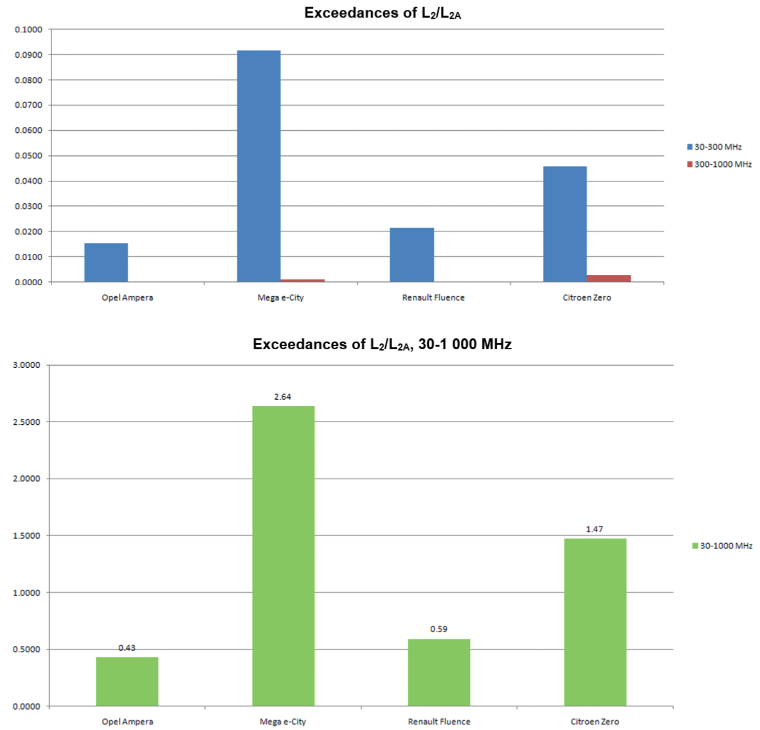


Fig. 13. Comparison of coefficients of excessive electromagnetic emission at EMC testing of electric vehicles
x-axis – vehicle
y-axis – coefficient of excessive electromagnetic emission

Table 6. Comparison of values of the coefficient of excessive electromagnetic emission determined during the EMC testing of electric vehicles

Item	VUT	Reference (limit) level L_2/L_{2A}					Ranking
		30-300 MHz		300-1000 MHz		Overall	
		Σf_{over} [MHz]	$k_{30\text{-}300}$ [%]	Σf_{over} [MHz]	$k_{300\text{-}1000}$ [%]	k [%]	
	1	2	3	4	5	6	7
1.	OPEL Ampera	4.1915	1.55	0	0.00	0.4321	1
2.	RENAULT Fluence	5.7451	2.13	0	0.00	0.5923	2
3.	CITROEN Zero	12.3163	4.56	1.9591	0.28	1.4717	3
4.	MEGA e-City	24.7374	9.16	0.8322	0.12	2.6360	4

The algorithm of computing the values of the coefficients of excessive electromagnetic emission for individual VUTs have been presented in Fig. 14.

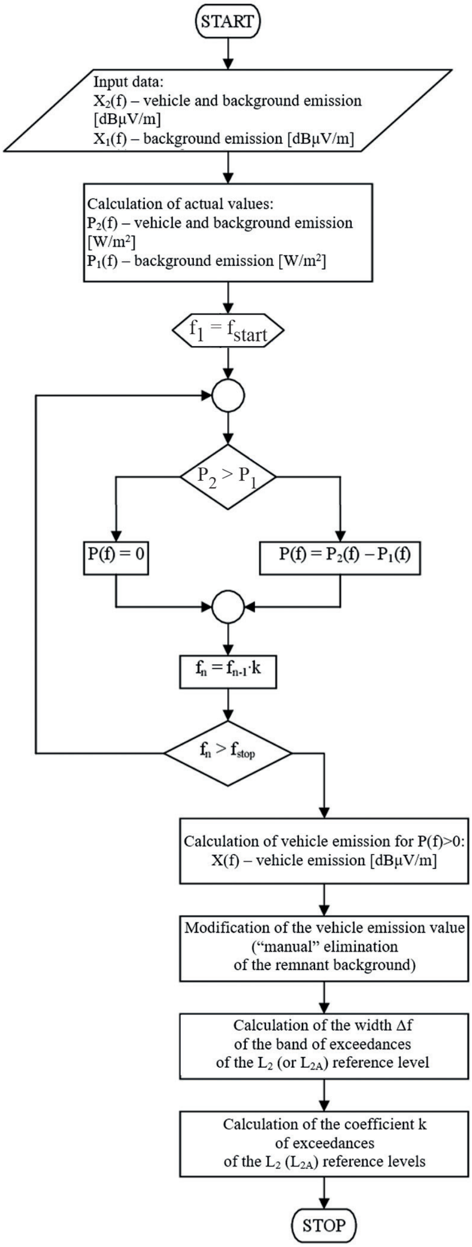


Fig. 14. Algorithm of computing the energy coefficients in the ML2+ method

3. EMR assessment by the two-line area-related method (MP2)

In this method, the electromagnetic compatibility of vehicles in respect of electromagnetic emission is assessed on the grounds of both the width of the band of exceedances of the L_2 and L_3 reference levels and the electromagnetic field intensity level in comparison with the L_1 limit lines. The level of vehicle electromagnetic emission is measured in this method by the areas between the recorded curves representing the actual electromagnetic emission and the limit (reference) lines L_1, L_2, and L_3. The assessment of electromagnetic emission level by the three-line area-related method has been illustrated in Figs 15 and 16.

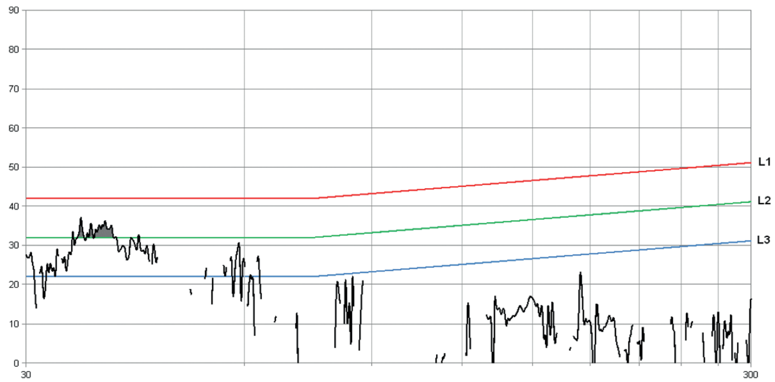


Fig. 15. Assessment of the electromagnetic emission of a vehicle based on the area between the recorded emission curve and the L_2 limit line

Fig. 16. Assessment of the electromagnetic emission of a vehicle based on the area between the recorded emission curve and the L_3 limit line

The areas between the recorded curves representing the actual electromagnetic emission and the limit (reference) lines L1, L2, and L3 are calculated according to a formula:

$$k_i = \frac{1}{\Delta F} \int_{f_{\min}}^{f_{\max}} (X - L_i) df \tag{7}$$

or, in the case of a discrete function:

$$k_i = \frac{1}{\Delta F} \sum_{k=1}^{N} (X_k - L_i), \text{ where } N \text{ is the size of the data array} \tag{8}$$

The calculations were carried out on data identical to those used in the two-line-plus method, with using a specially prepared computer program.

As the L_1/L_{1A} reference levels, the limit levels defined in UN ECE Regulation No 10.04 were adopted. The L_2/L_{2A} levels were adopted as follows, similarly as in the two-line-plus method:

1) $L_2 = L_1$ – 10 dB for the antenna-VUT distance of 3 m;
2) $L_{2A} = L_{1A}$ – 8 B for the antenna-VUT distance of 10 m.

For the L_3/L_{3A} levels, a rule similar to that used in the two-line-plus method was adopted, i.e.:

3) $L_3 = L_2$ – 10 dB for the antenna-VUT distance of 3 m;
4) $L_{3A} = L_{2A}$ – 8 B for the antenna-VUT distance of 10 m.

The calculation results have been presented in Tables 7-10.

Table 7.

OPEL Ampera			
	L_1	L_2	L_3
30-300 MHz	–35.9352	0.0569	0.8143
300-1 000 MHz	–37.4028	0.0000	0.0000

Table 8.

RENAULT Fluence			
	L_{1A}	L_{2A}	L_{3A}
30-300 MHz	–20.2057	0.0735	1.0821

Table 9.

CITROEN Zero			
	L_{1A}	L_{2A}	L_{3A}
30-300 MHz	−23.6186	0.2203	1.4269
300-1 000 MHz	−24.3279	0.0138	0.1217

Table 10.

MEGA e-City			
	L_1	L_2	L_3
30-300 MHz	−23.8429	0.3398	2.5052
300-1 000 MHz	−25.9069	0.0019	0.4500

The EMR assessment results obtained with using the area-related methods have been presented in the form of bar graphs in Figs 17, 18 and 19.

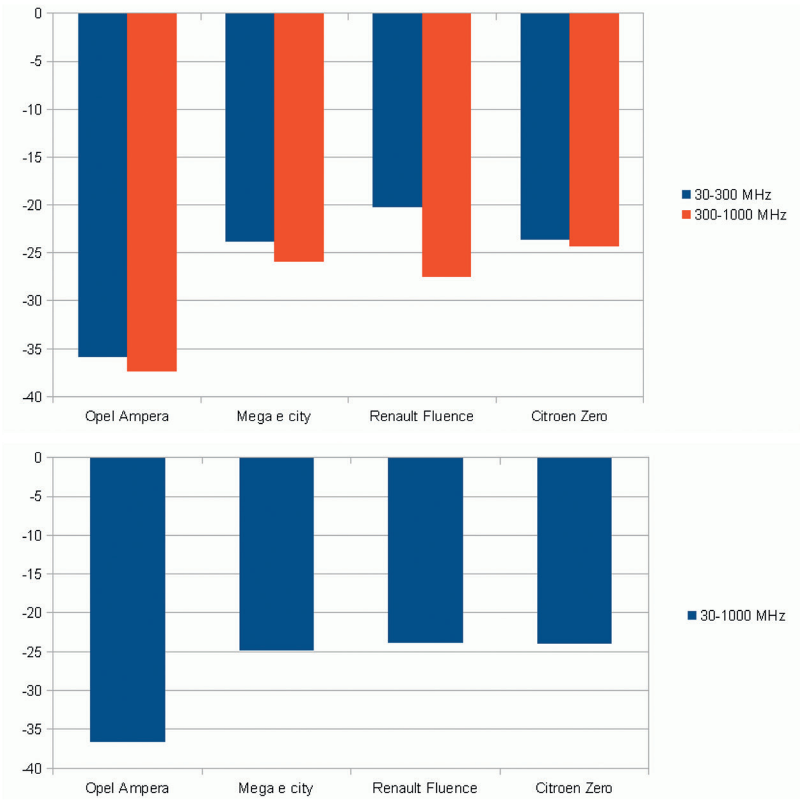


Fig. 17. Comparison of the areas between the recorded electromagnetic emission curves and the L_1/L_{1A} limit line (for explanations see the text)

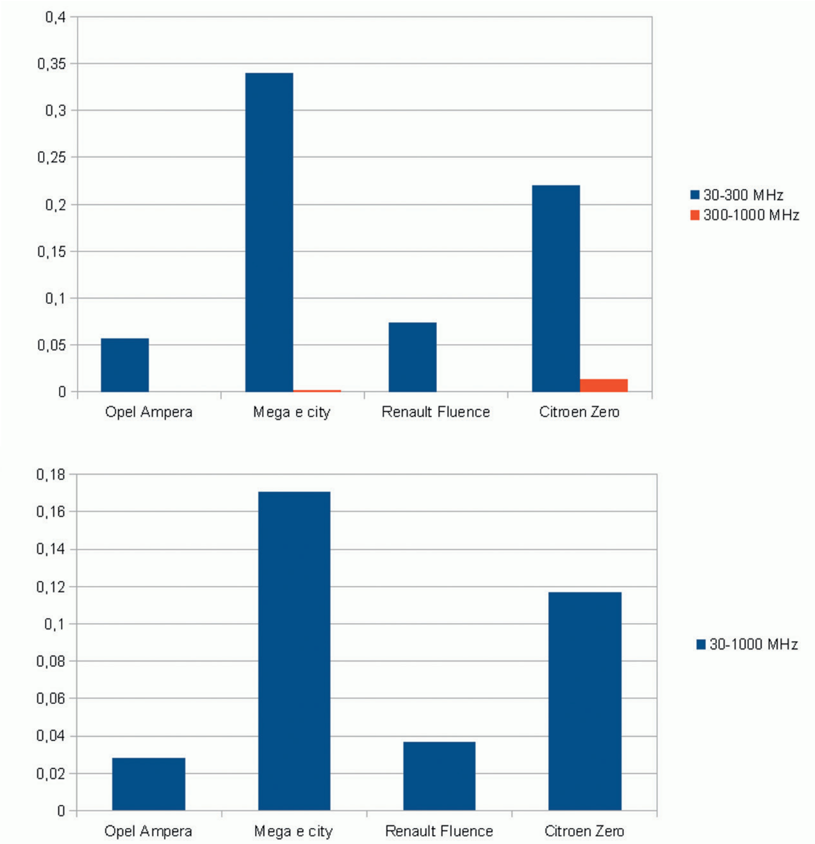
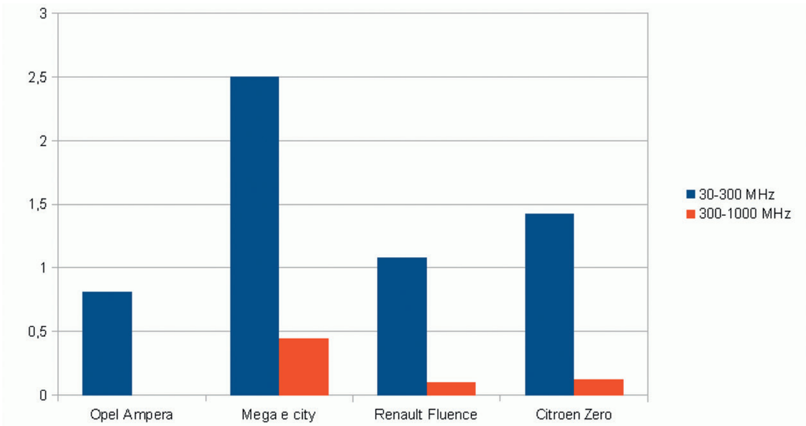


Fig. 18. Comparison of the areas between the recorded electromagnetic emission curves and the L_2/L_{2A} limit line (for explanations see the text)



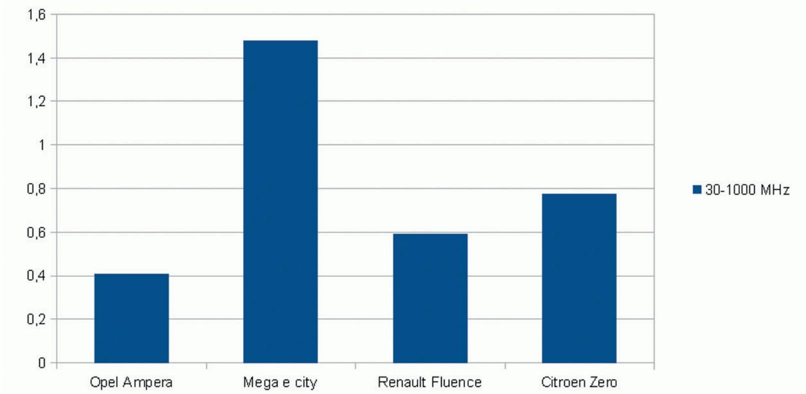


Fig. 19. Comparison of the areas between the recorded electromagnetic emission curves and the L_3/L_{3A} limit line (for explanations see the text)

4. EMR assessment by the parameter estimation method (MEP)

The EMC of vehicles in respect of electromagnetic emission was also assessed by the parameter estimation method (MEP). In the calculations, estimators of the following parameters related to power of the electromagnetic signal emitted were taken into account:

a) estimator of average value $\bar{X}$;
b) estimator of quadratic average value X^2;
c) estimator of variance W;
d) estimator of root-mean-square value RMS;
e) estimator of standard deviation S;
f) estimator of amplitude A.

The calculations were carried out on data identical to those used in the two-line-plus method (ML2+) and the three-line area-related method (MP3+), with using a specially prepared computer program. The estimators were calculated after the electromagnetic field intensity values obtained from measurements had been converted from logarithmic into linear scale.

The following formulas were used for the calculations:

– estimator of average value
$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{9}$$

– estimator of quadratic average value
$$X^2 = \frac{1}{N}\sum_{i=1}^{N} x_i^2 \tag{10}$$

– estimator of variance
$$W = \frac{1}{N-1}\sum_{i=1}^{N} \left(x_i - \overline{X}\right)^2 \tag{11}$$

– estimator of root-mean-square value
$$RMS = \sqrt{X^2} \tag{12}$$

– estimator of standard deviation
$$S = \sqrt{W^2} \tag{13}$$

– estimator of amplitude
$$A = \overline{X} + S \tag{14}$$

The above estimators were also calculated for the L_1, L_2/L_{2A}, and L_3/L_{3A} levels.

As the L_1/L_{1A} reference levels, the limit levels defined in UN ECE Regulation No 10.04 were adopted. The L_2/L_{2A} levels were adopted as follows, similarly as in the two-line-plus method and in the three-line area-related method:

5) $L_2 = L_1$ – 10 dB for the antenna-VUT distance of 3 m;
6) $L_{2A} = L_{1A}$ – 8 B for the antenna-VUT distance of 10 m.

For the L_3/L_{3A} levels, a rule was adopted that was similar to that followed in the two-line-plus method and in the three-line area-related method, i.e.:

7) $L_3 = L_2$ – 10 dB for the antenna-VUT distance of 3 m;
8) $L_{3A} = L_{2A}$ – 8 B for the antenna-VUT distance of 10 m.

The calculation results have been summarized in Table 11.

Table 11.

Signal analysed	X	X^2	W	RMS	S	A	d
OPEL Ampera	7.14E-013	3.40E-024	2.90E-024	1.85E-012	1.70E-012	2.42E-012	
MEGA e-City	3.36E-012	3.90E-023	2.77E-023	6.25E-012	5.27E-012	8.63E-012	
L_1	3.04E-010	1.38E-019	4.51E-020	3.71E-010	2.12E-010	5.16E-010	3 m
L_2	3.04E-011	1.38E-021	4.51E-022	3.71E-011	2.12E-011	5.16E-011	
L_3	3.04E-012	1.38E-023	4.51E-024	3.71E-012	2.12E-012	5.17E-012	
RENAULT Fluence	1.53E-013	1.68E-025	1.45E-025	4.10E-013	3.80E-013	5.33E-013	
CITROEN Zero	3.75E-013	8.51E-025	7.12E-025	9.23E-013	8.44E-013	1.22E-012	
L_{1A}	3.04E-011	1.38E-021	4.51E-022	3.71E-011	2.12E-011	5.16E-011	10 m
L_{2A}	4.82E-012	3.46E-023	1.13E-023	5.88E-012	3.37E-012	8.19E-012	
L_{3A}	7.64E-013	8.69E-025	2.85E-025	9.32E-013	5.34E-013	1.30E-012	

Afterwards, the estimators of specific parameters for individual vehicles were converted to a form relative to the corresponding parameters for the limit lines, according to the formula:

$$E = \frac{E_p}{E_{Li}} \tag{15}$$

where: $E \in \{\overline{X}, X^2, W, RMS, S, A\}$ – the relative estimator being calculated;

E_p – estimator of a specific parameter for an individual vehicle;

E_{Li} – estimator of the parameter for the limit line and i = 1...3.

Figs 20, 21 and 22 show graphs representing the estimators calculated for the vehicles under test in relation to the L_1, L_2, and L_3 limit lines.

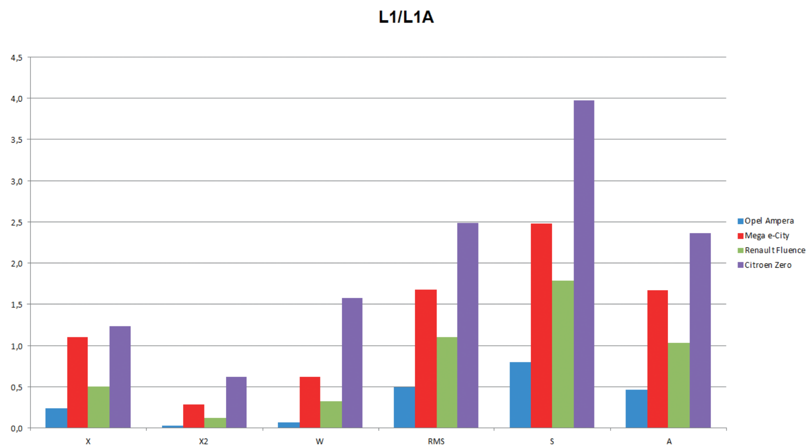


Fig. 20. Estimators of specific parameters for individual vehicles relative to the corresponding parameters for the L_1/L_{1A} limit line (for explanations see the text)

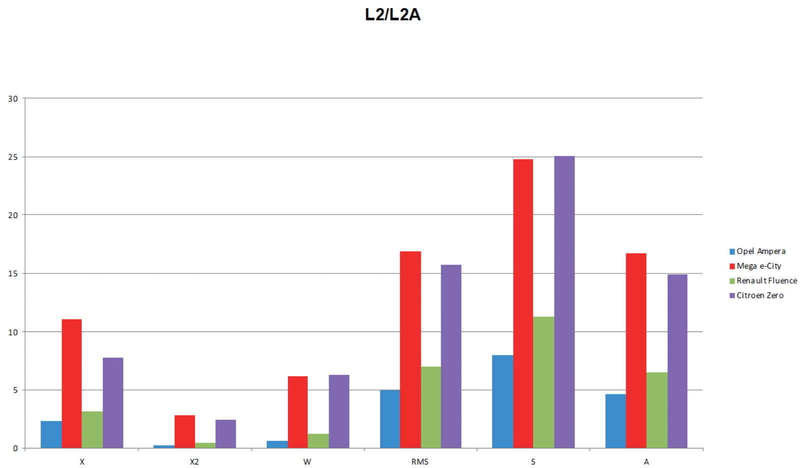


Fig. 21. Estimators of specific parameters for individual vehicles relative to the corresponding parameters for the L_2/L_{2A} limit line (for explanations see the text)

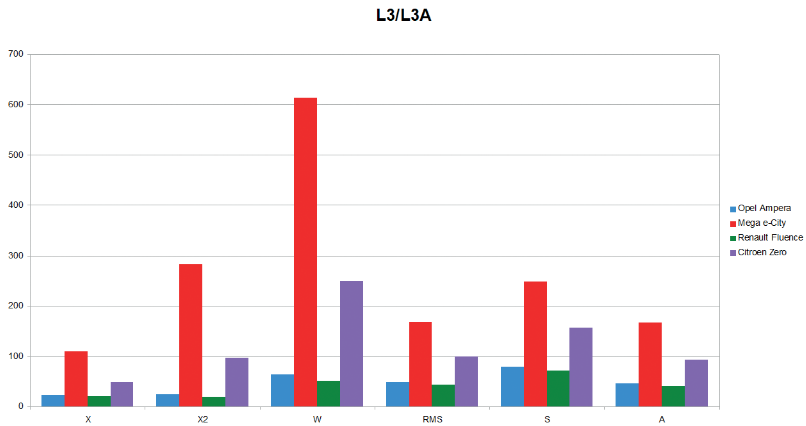


Fig. 22. Estimators of specific parameters for individual vehicles relative to the corresponding parameters for the L_3/L_{3A} limit line (for explanations see the text)

5. Analysis of the EMR assessment of the vehicles

The electromagnetic compatibility of vehicles in respect of electromagnetic emission was assessed with using three methods:

a) two-line-plus method (ML2+);

b) area-related method (MP);

c) parameter estimation method (MEP).

The calculation results obtained with using individual methods are comparable with each other. In particular, attention is deserved by strong correlation between calculation results obtained for methods ML2+, MP, and MEP (estimators of average value, RMS value, and amplitude) in relation to the L_2/L_{2A} reference line, illustrated in Table 12 and in Figs 23 and 24.

Table 12. Summary of the results of calculation of the coefficient of excessive electromagnetic emission in relation to the L_2/L_{2A} reference line for individual methods

Vehicle	ML2+	ML3P	MEP		
			RMS	A	X
OPEL Ampera	0.43	0.03	0.05	0.05	0.02
MEGA e-City	2.64	0.17	0.17	0.17	0.11
RENAULT Fluence	0.59	0.04	0.07	0.07	0.03
CITROEN Zero	1.47	0.12	0.16	0.15	0.08

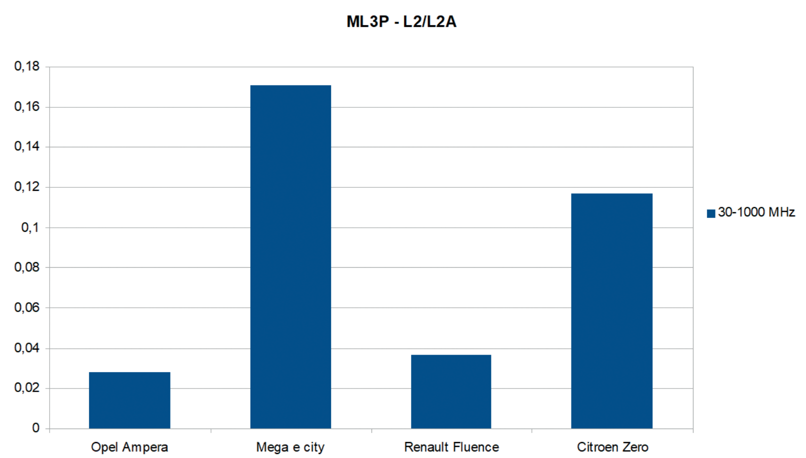


Fig. 23. Coefficient of excessive electromagnetic emission in relation to the L_2/L_{2A} reference line for the ML3P method (for explanations see the text)

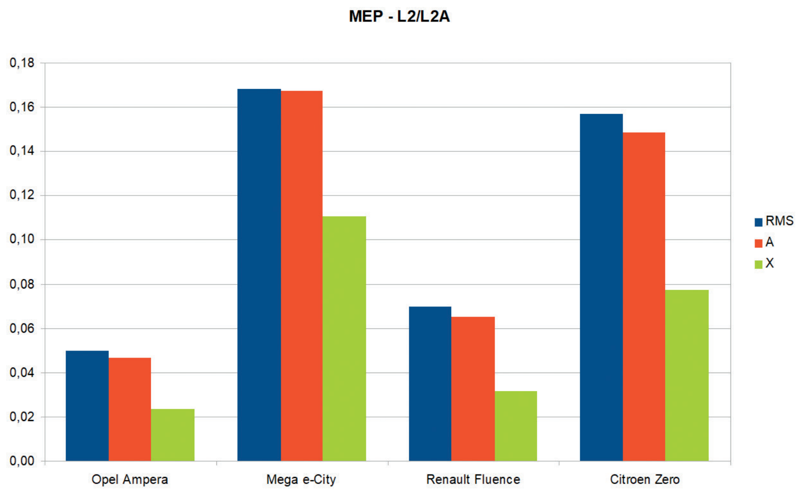


Fig. 24. Coefficient of excessive electromagnetic emission in relation to the L_2/L_{2A} reference line for the MEP method (estimators of average value, RMS value, and amplitude) (for explanations see the text)

6. Recapitulation

The electromagnetic compatibility (EMC) of motor vehicles, in particular electrically driven, is an important element among those subject to assessment. The qualitative optimization of the parameters that can influence the assessment, primarily a reduction in the electromagnetic radiation (EMR) of the vehicle under consideration, will not only result in correct functioning of the vehicle but also will help to avoid possible harmful impact of EMR on vehicle occupants' health. The assessment criteria given in normative documents (UN ECE Regulation No 10 and Directive 72/245/EEC), based on the limit values specified there, are the minimum acceptability requirements. No quality criteria exist that would make it possible to analyse and assess the EMR of motor vehicles in EMC tests.

In this article, the EMC requirements for motor vehicles and their equipment have been presented. The EMR testing methods, based on the normative documents mentioned above and providing grounds for approving specific vehicle types for production and operation (type approval), have also been described. Three groups of methods, i.e. line methods, area-related methods, and parameter estimation methods, have been proposed and described in part I of this article for the EMR assessment of vehicles. Based on the EMR tests carried out at PIMOT on a few electric vehicles (EV), the EMR of the vehicles was analysed and assessed with using some of the said methods. The following vehicles were used for the analyses and calculations: OPEL Ampera, RENAULT Fluence, CITROEN C-Zero, and MEGA e-City.

The EMR of these vehicles was analysed and assessed with using the following methods from among the groups of methods proposed and described in part I of this article:

- two-line-plus method (ML2+);
- two-line area-related method (MP2);
- parameter estimation method (MEP).

The calculations carried out were based on the EMR curves actually recorded for the vehicles under test and referred to the L1, L2, and L3 limit lines defined in part I of this article.

The L1 reference (limit) line represents the minimum requirements that must be met by the vehicle under test; it has been defined by the type-approval regulations in force [1, 2].

The EMR analysis and assessment methods presented with the four EVs under test being taken as an example have been compared with each other in Section 5, with using the coefficient of excessive electromagnetic emission defined in this article. The figures in Table 12 in Section 5 unequivocally show an identical ranking of the values of this coefficient determined by each of these methods, which indicates a strong correlation between them. The best and worst results were obtained for OPEL Ampera and MEGA e-City, respectively. An inconvenience of the methods used is the quite complicated mathematical apparatus; however, it will most likely be possible to simplify it in the "engineering works" to follow, based on the experience gained.

The analysis and calculations carried out have revealed a close similarity between the usability of the proposed methods of EMR assessment of motor vehicles.

The work outputs may be utilized and disseminated, especially by the designers and researchers who are involved in work on motor vehicles, in particular EVs, where lots of electronic systems and modules are present.

The full text of the article is available in Polish online on the website
http://archiwummotoryzacji.pl.

Tekst artykułu w polskiej wersji językowej dostępny jest na stronie
http://archiwummotoryzacji.pl.

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